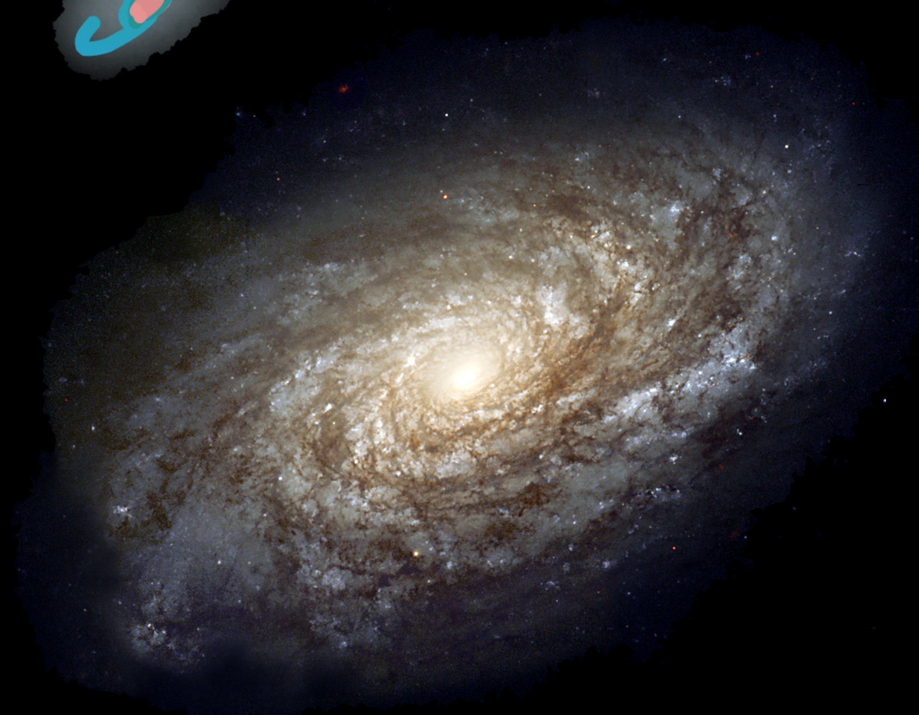
# Looking Ahead: Circumgalactic Metals and Gas with HST and LUVOIR

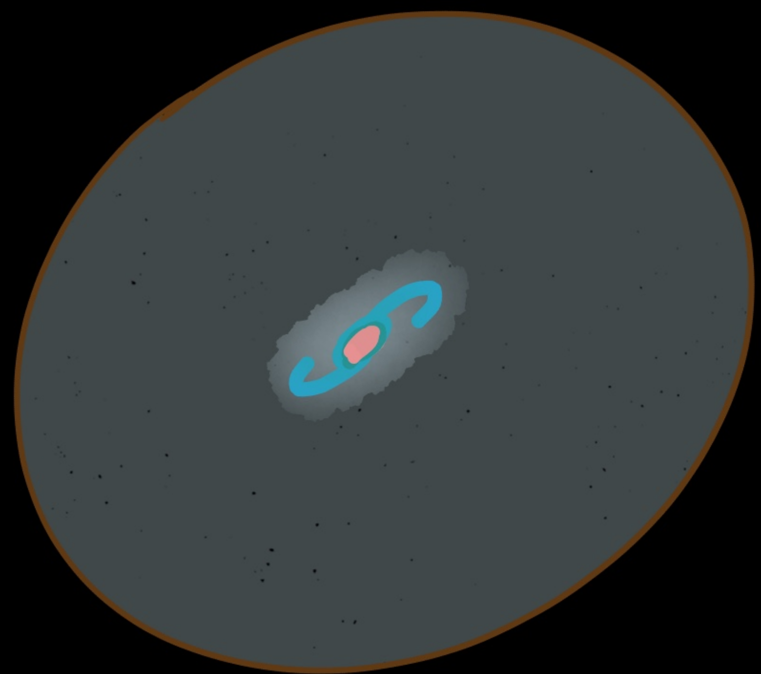
J. Christopher Howk
*University of Notre Dame*
*/ Universidad Católica*

# Looking Ahead: Circumgalactic Metals and Gas with HST and LUVOIR

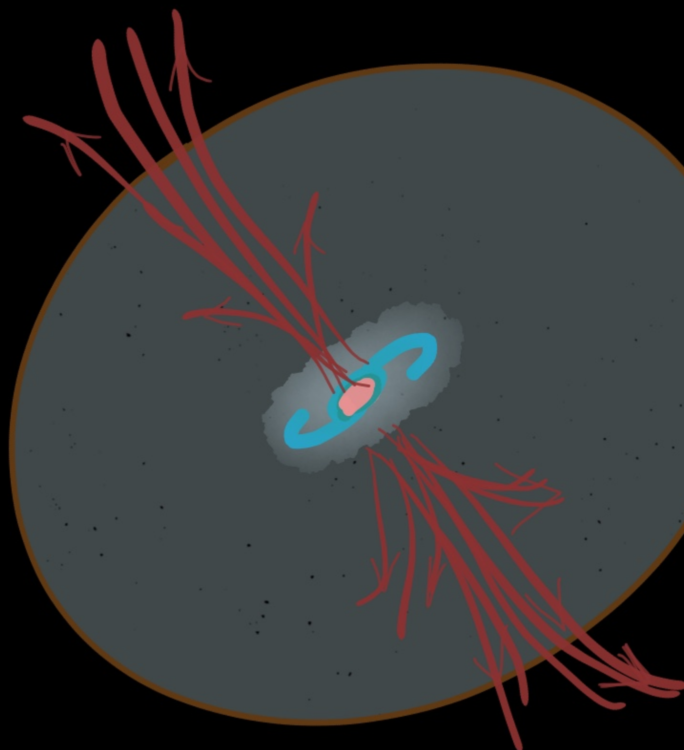
J. Christopher Howk
*University of Notre Dame*
*/ Universidad Católica*

The visible **stars** in a galaxy trace only a portion of the baryonic matter important to its evolution.





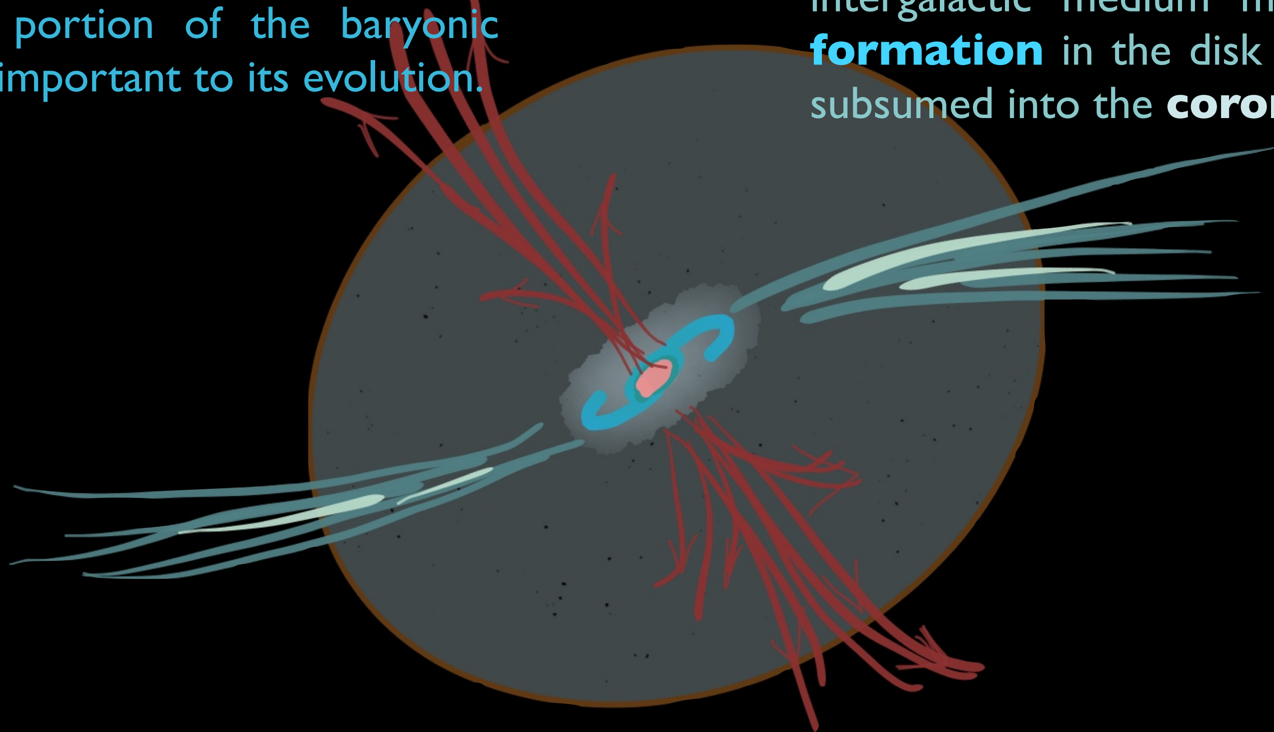
An extended **corona** of gas may be a remnant of the collapse of the galaxy, perhaps at the virial temperature of the dark matter halo.



Outflows driven by star formation and/or AGN activity circulate **baryons, metals,** and **energy** into the **corona** (and perhaps beyond the halo).

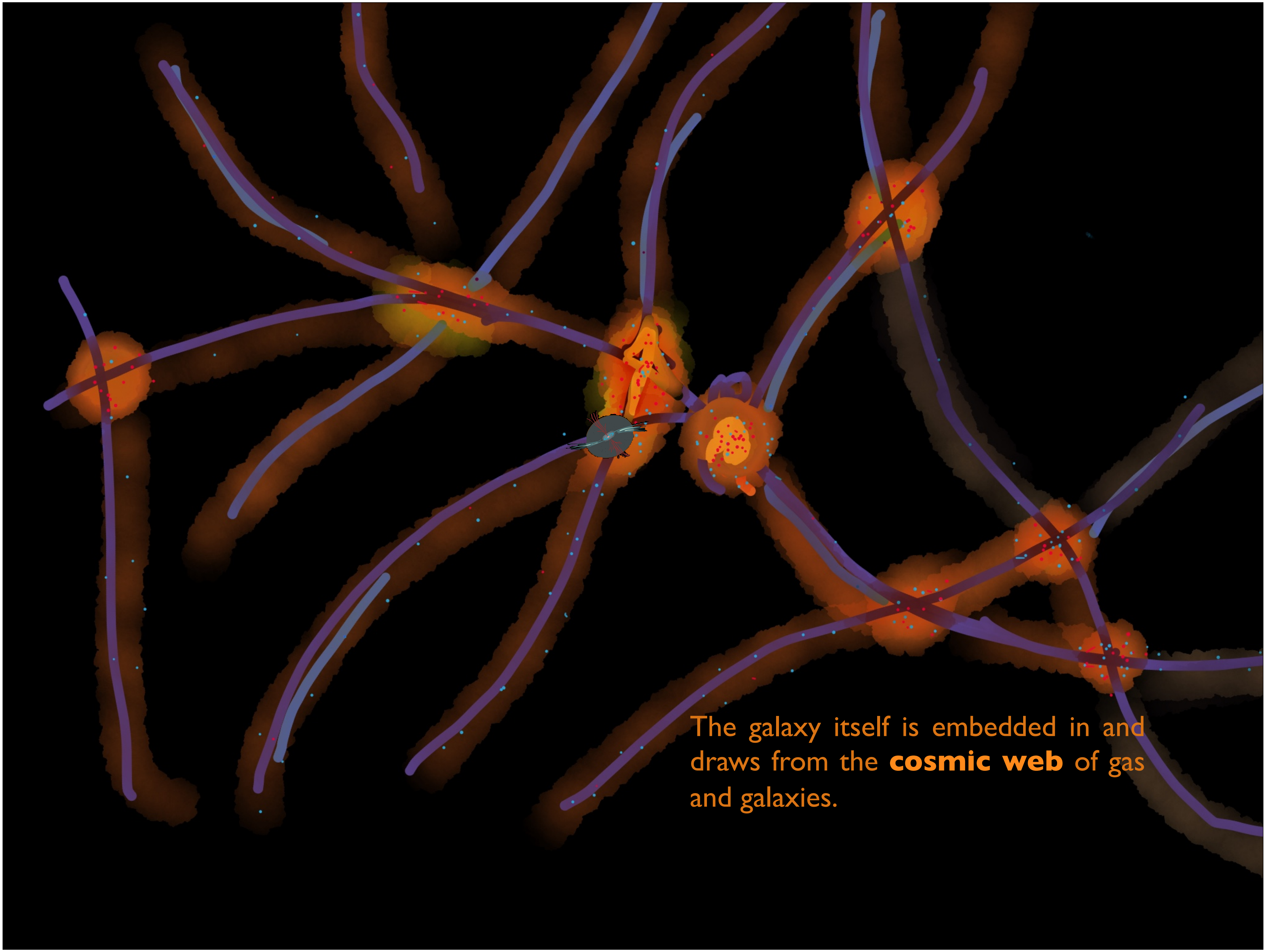
The visible **stars** in a galaxy trace only a portion of the baryonic matter important to its evolution.

Inflowing **pristine matter** from the intergalactic medium may fuel **star formation** in the disk or be heated, subsumed into the **corona**.

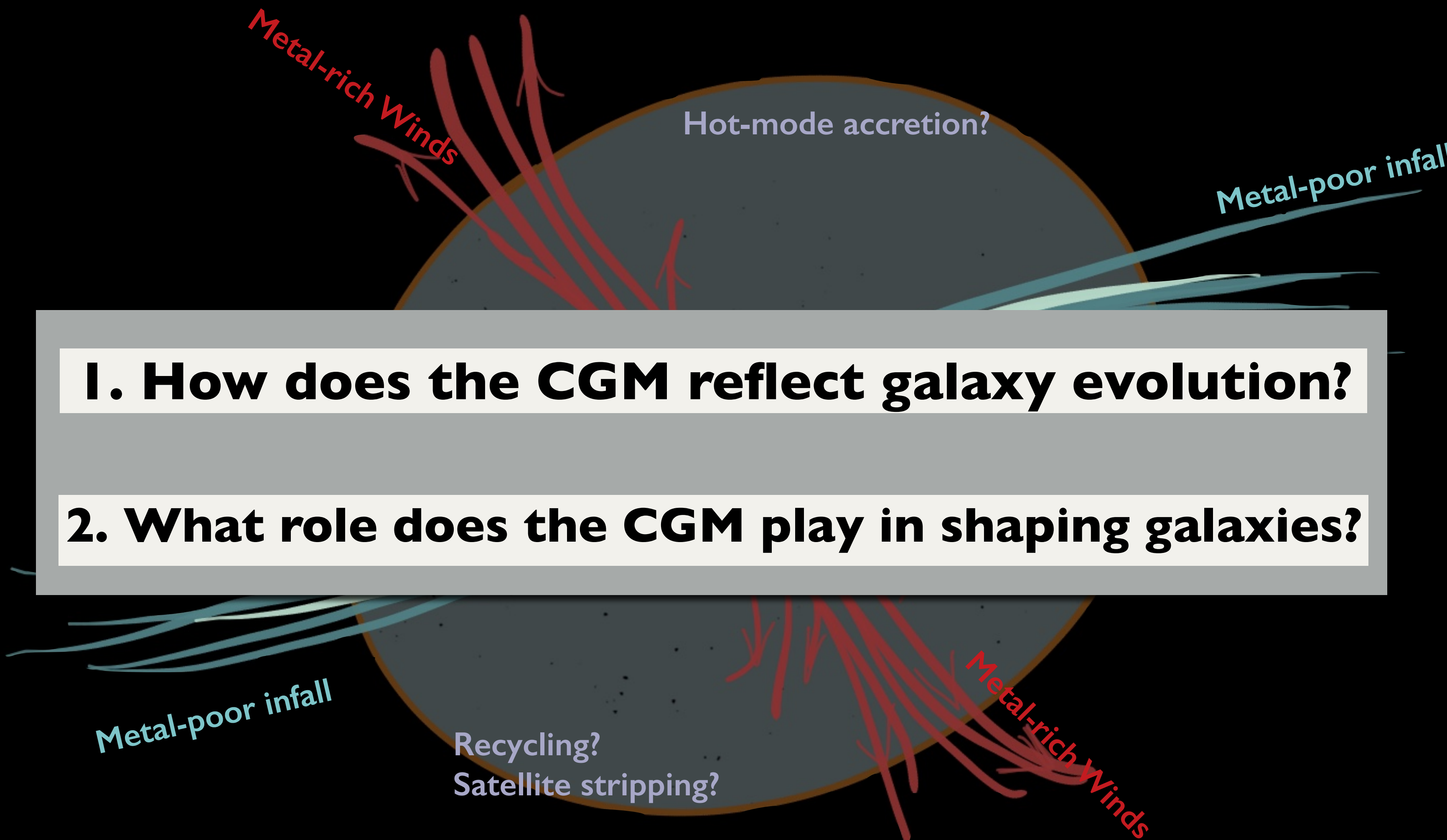


Outflows driven by star formation and/or AGN activity circulate **baryons, metals,** and **energy** into the **corona** (and perhaps beyond the halo).

An extended **corona** of gas may be a remnant of the collapse of the galaxy, perhaps at the virial temperature of the dark matter halo.

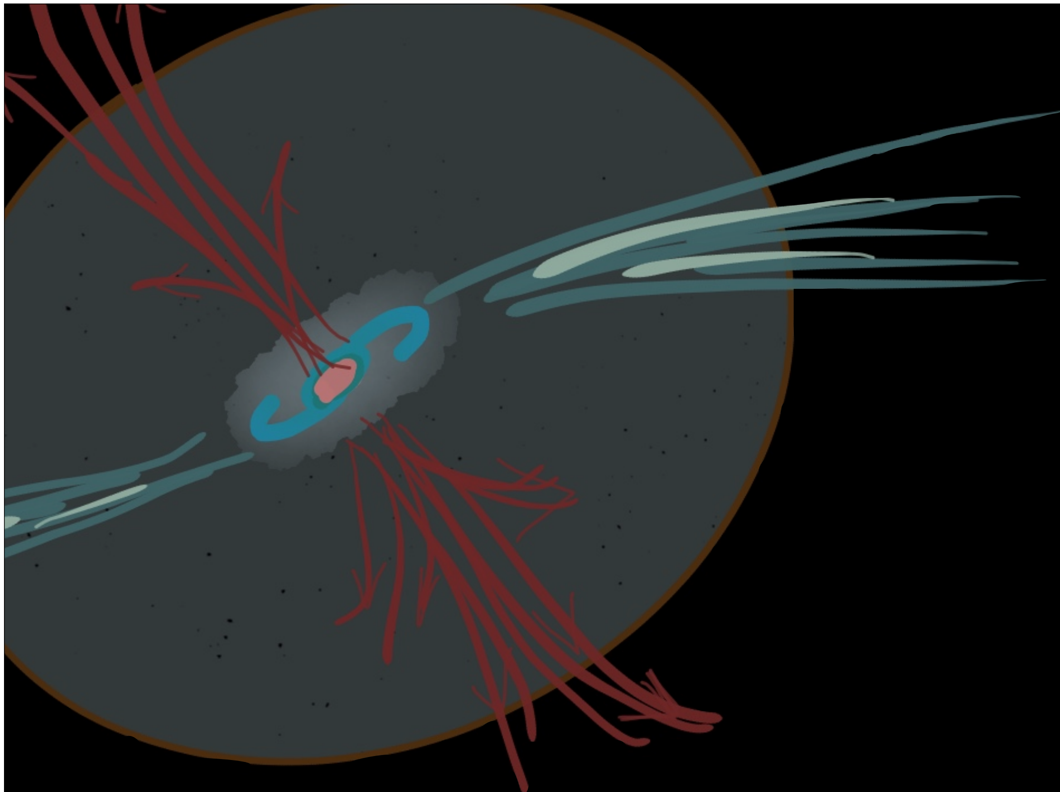

The galaxy itself is embedded in and draws from the **cosmic web** of gas and galaxies.

The CGM plays a ***fundamental role*** in and potentially provides ***unique constraints*** on galaxy evolution.




**1. How does the CGM reflect galaxy evolution?**

**2. What role does the CGM play in shaping galaxies?**



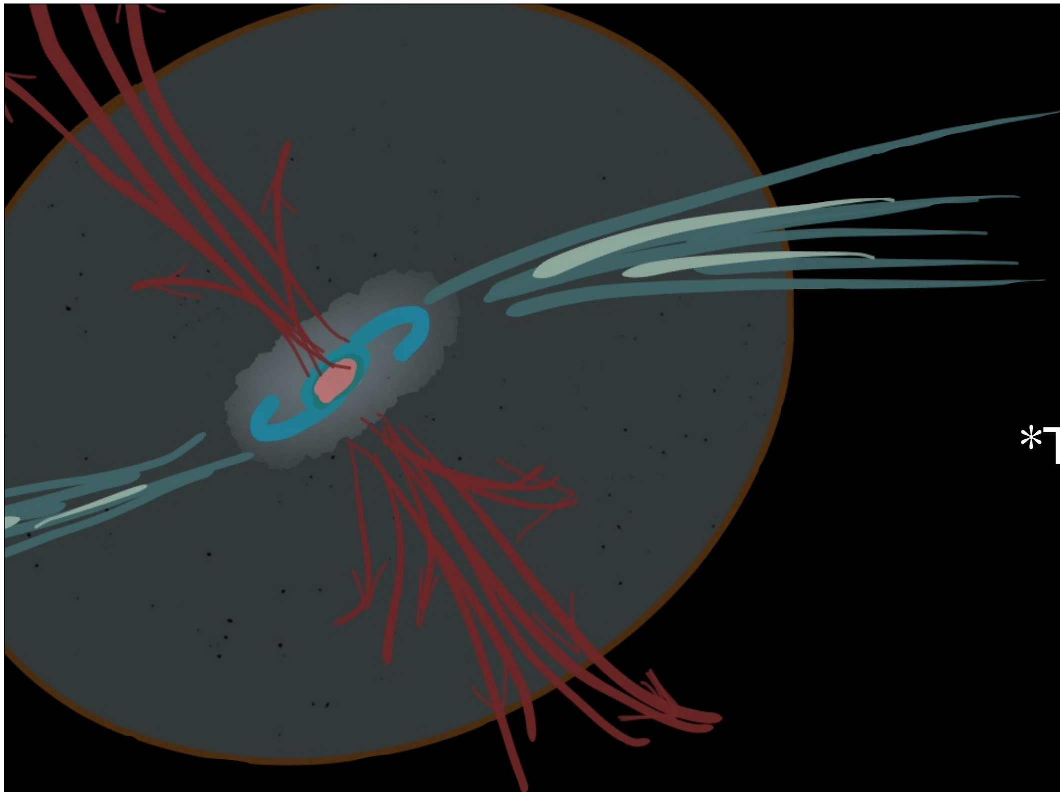
## 1. How does the CGM reflect galaxy evolution?

The baryonic and metal content of the CGM trace matter collected from the assembly of the galaxy & matter expelled from the galaxy.

Recycling?
Satellite stripping?

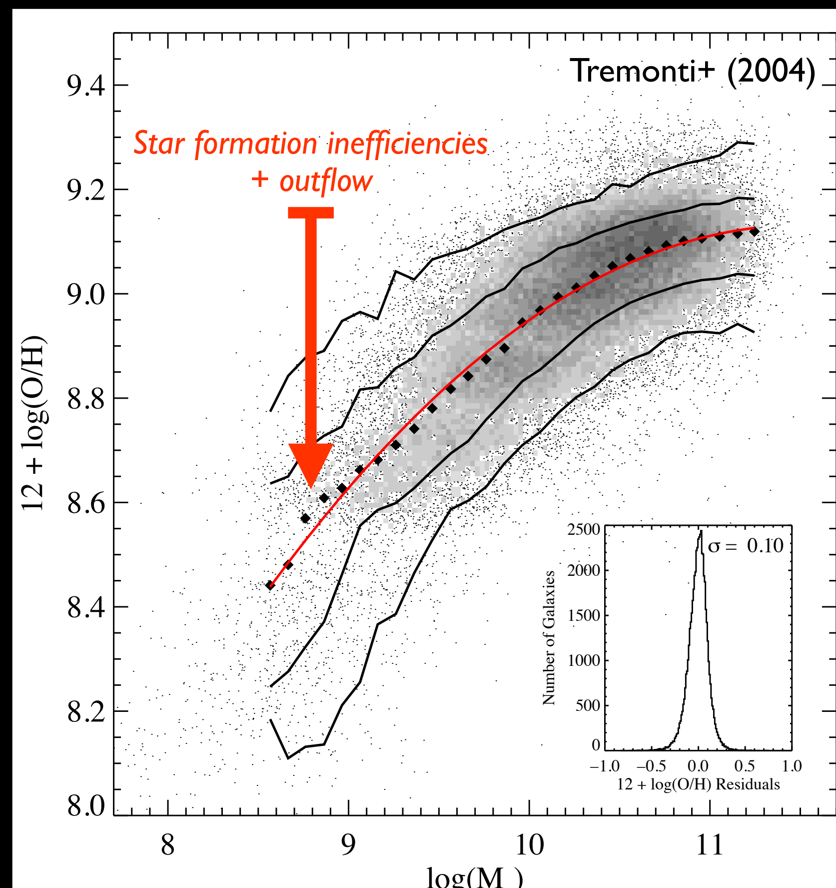
Hot-mode accretion?

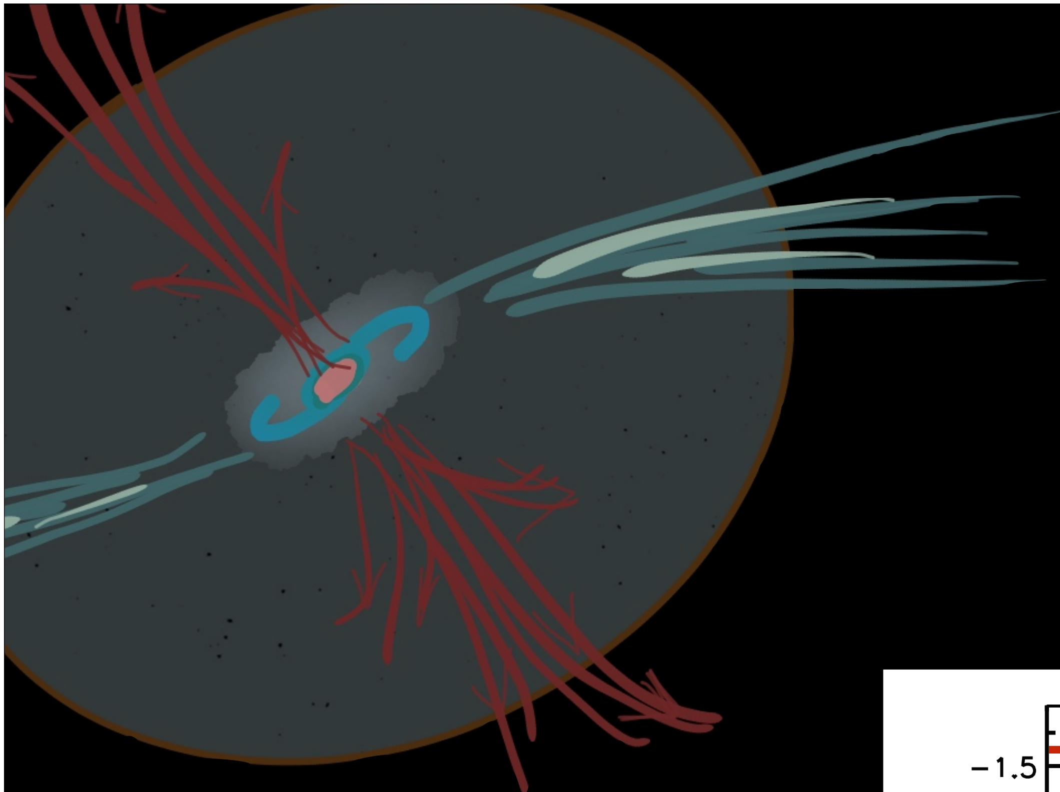
Primordial corona?



# 1. How does the CGM reflect galaxy evolution?

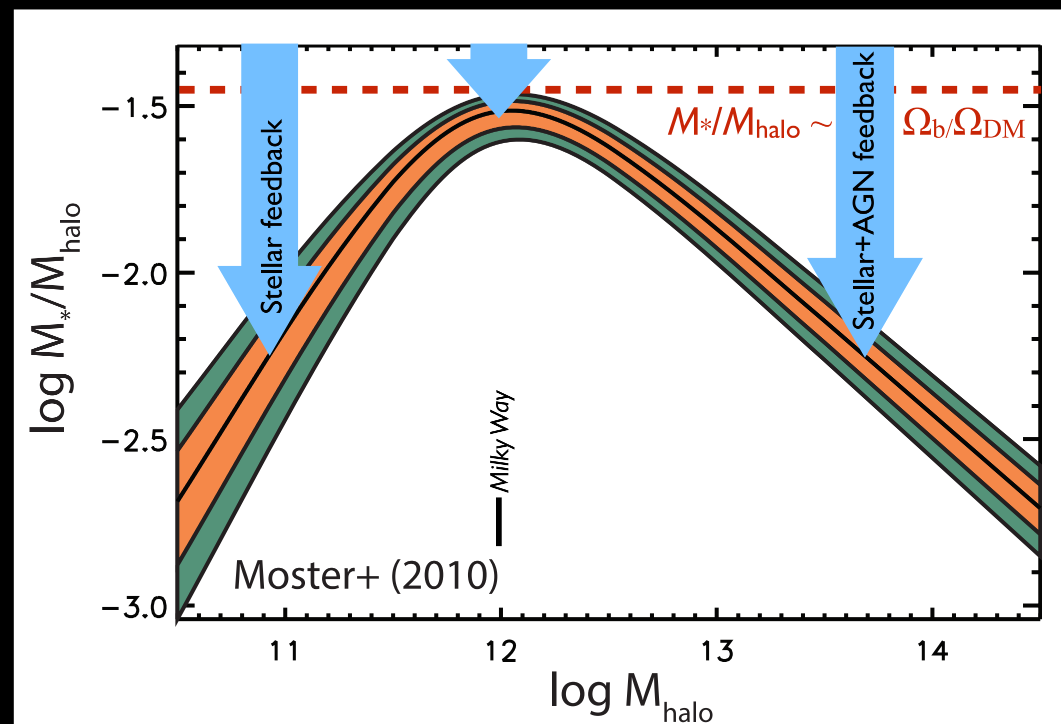
*The galactic mass-metallicity relationship may be shaped by galactic outflows.

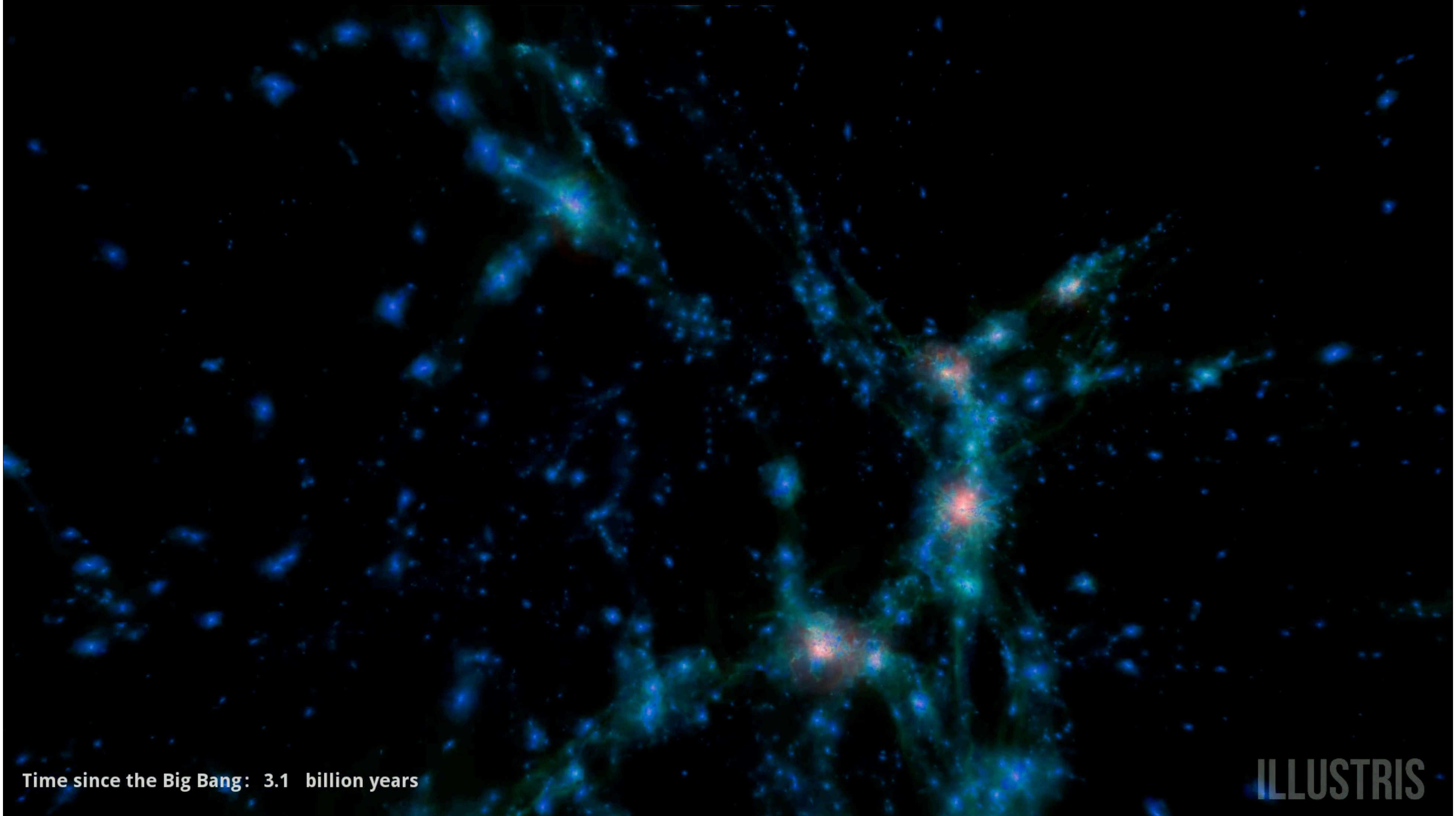




# 1. How does the CGM reflect galaxy evolution?

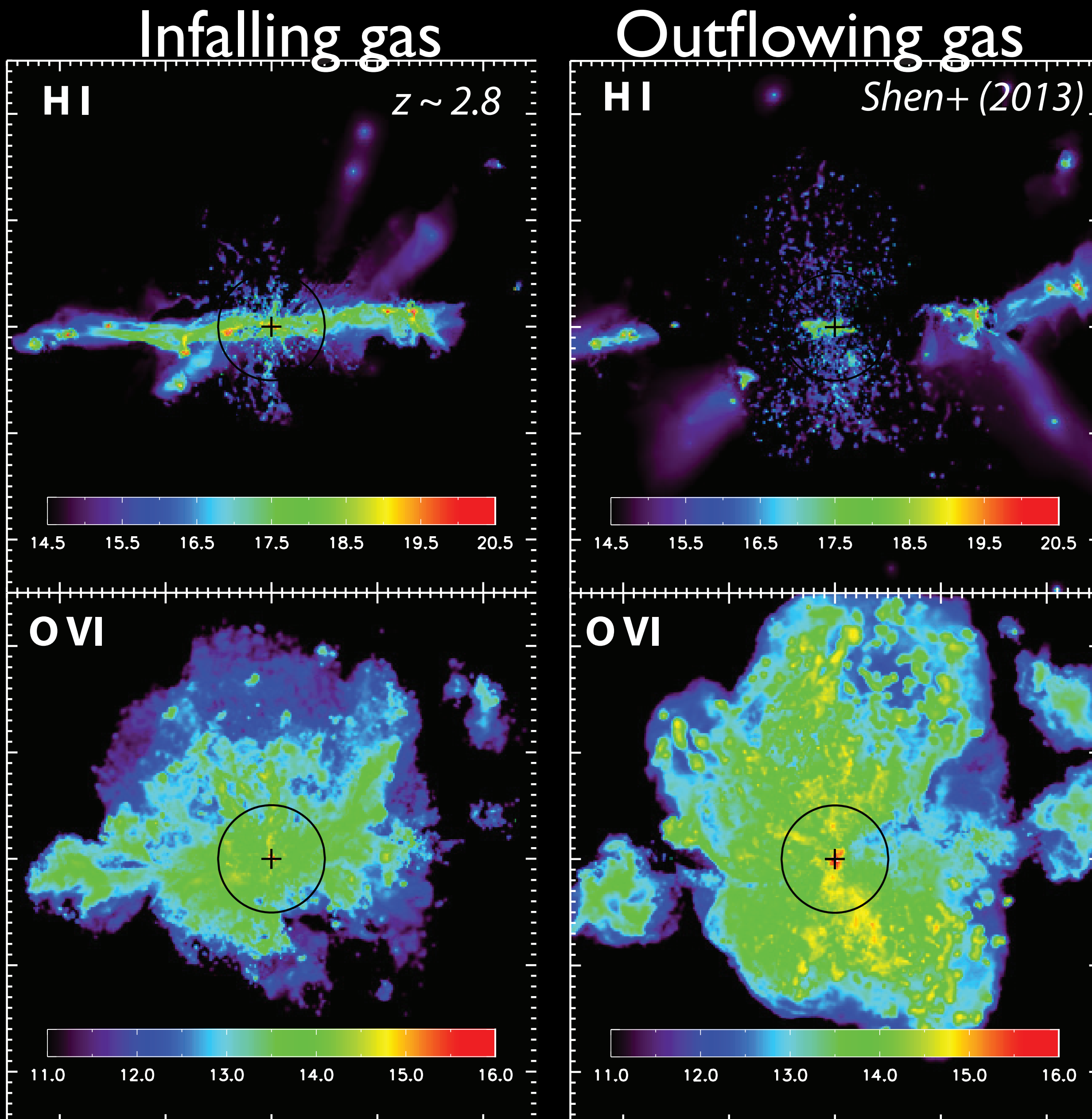
*The CGM may host a significant number of "invisible" baryons.



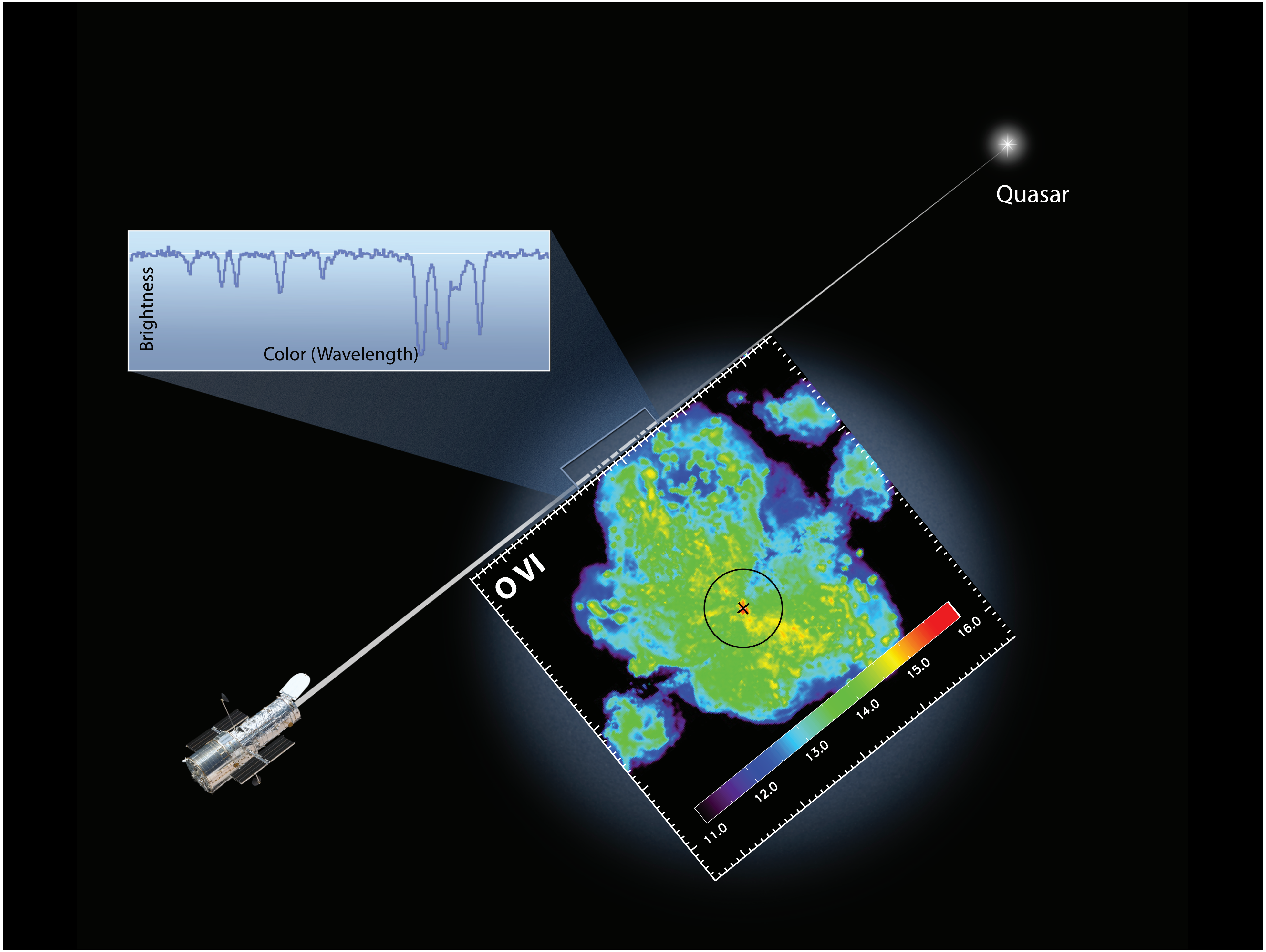



cold warm hot

*ILLUSTRIS simulations:* Vogelsberger+ (2014)

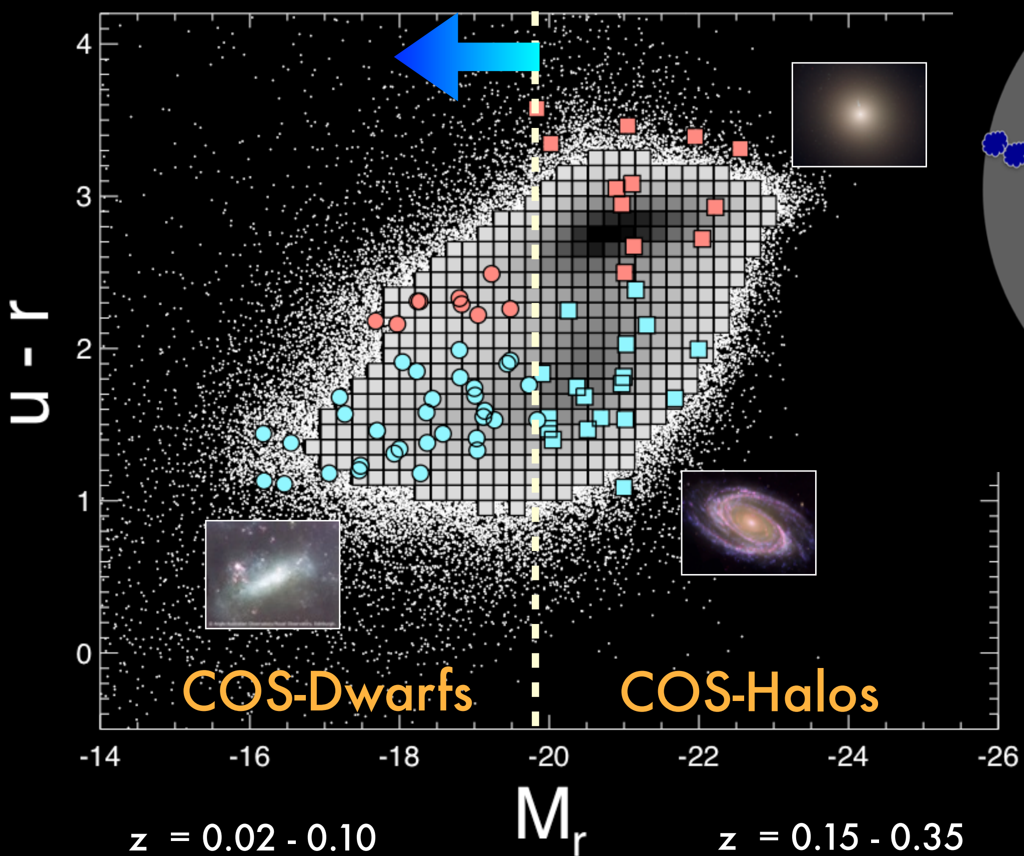


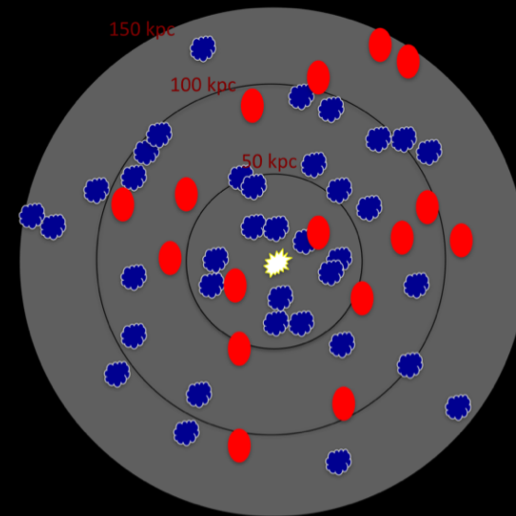

Projected H I and O VI column densities (units: atoms $cm^{-2}$)



Quasar
Brightness
Color (Wavelength)
O VI
11.0
12.0
13.0
14.0
15.0
16.0

# COS-Halos survey studied CGM vs. galaxy properties




"Map" of QSOs relative to foreground galaxies.

z = 0.02 - 0.10
logM* = 8 - 10
optimal for CIV

z = 0.15 - 0.35
logM* = 10 - 11.5
optimal for OVI

ALL GALAXIES SELECTED PRIOR TO ABSORPTION

Slide courtesy of J. Tumlinson

# The CGM harbors a large fraction of galactic baryons

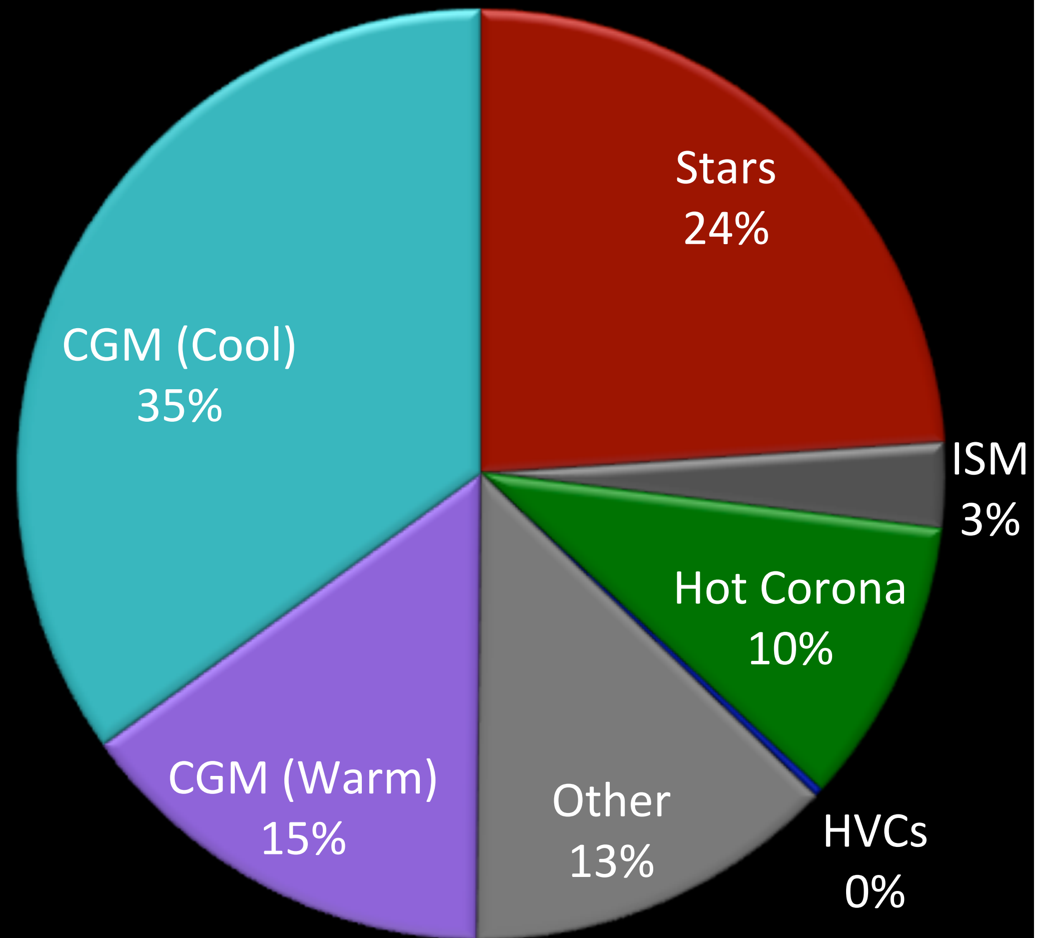
## Cool+Warm CGM mass budget:

Typical mass of cool gas in CGM:
$M_{\mathrm{Cool\ CGM}} \sim 6 \times 10^{10}\ M_{\odot}$

Typical mass of warm gas in CGM:
$M_{\mathrm{Warm\ CGM}} \sim 2 \times 10^{10}\ M_{\odot}$

*There is probably not a galactic "missing baryons problem."*

**Baryon budget of typical L* galaxy (~$10^{12}\ M_{\odot}$)**




**Werk+ (2014);**
also Stocke+ (2013), Lehner+ (2015), Keeney+ (2017)

# The CGM harbors a large fraction of galactic baryons

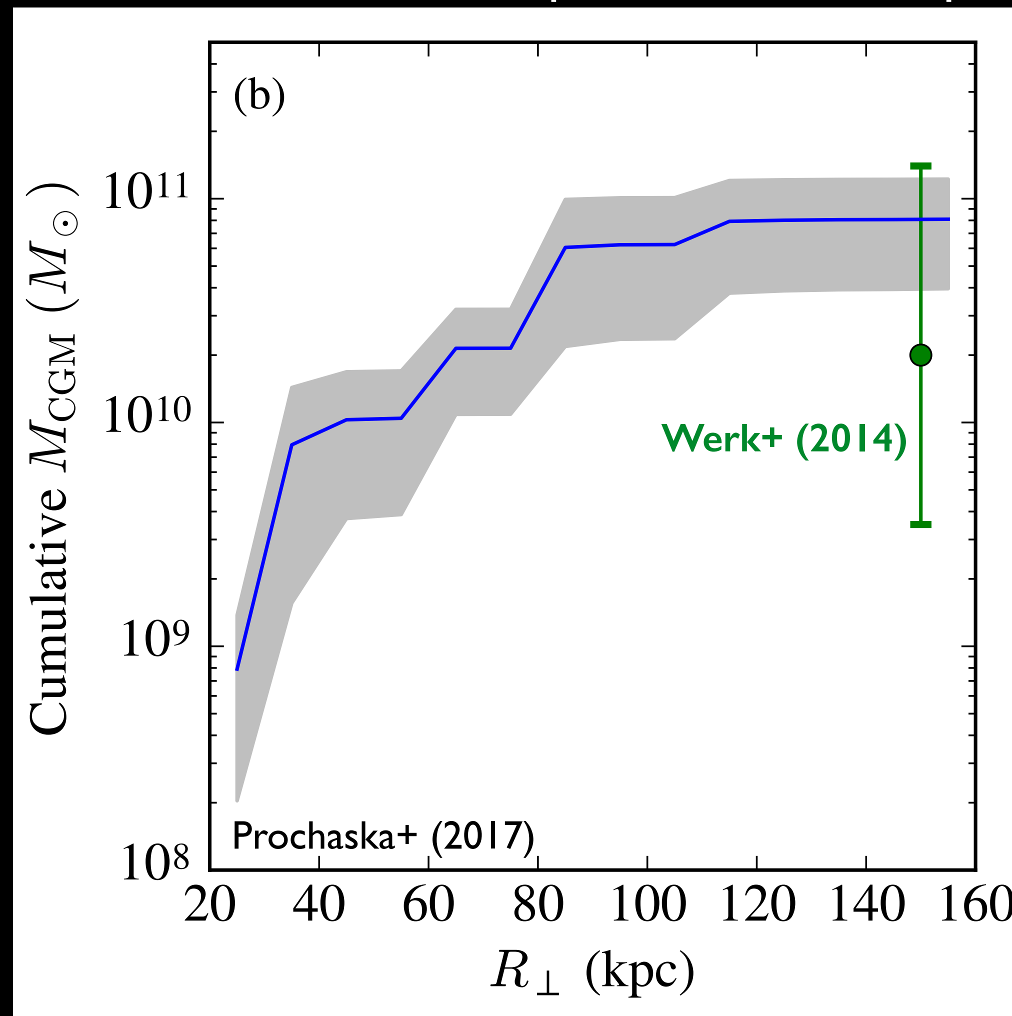
**Cool+Warm CGM mass budget:**

Typical mass of cool gas in CGM:
$M_{\text{Cool CGM}} \sim 6 \times 10^{10}\ M_\odot$

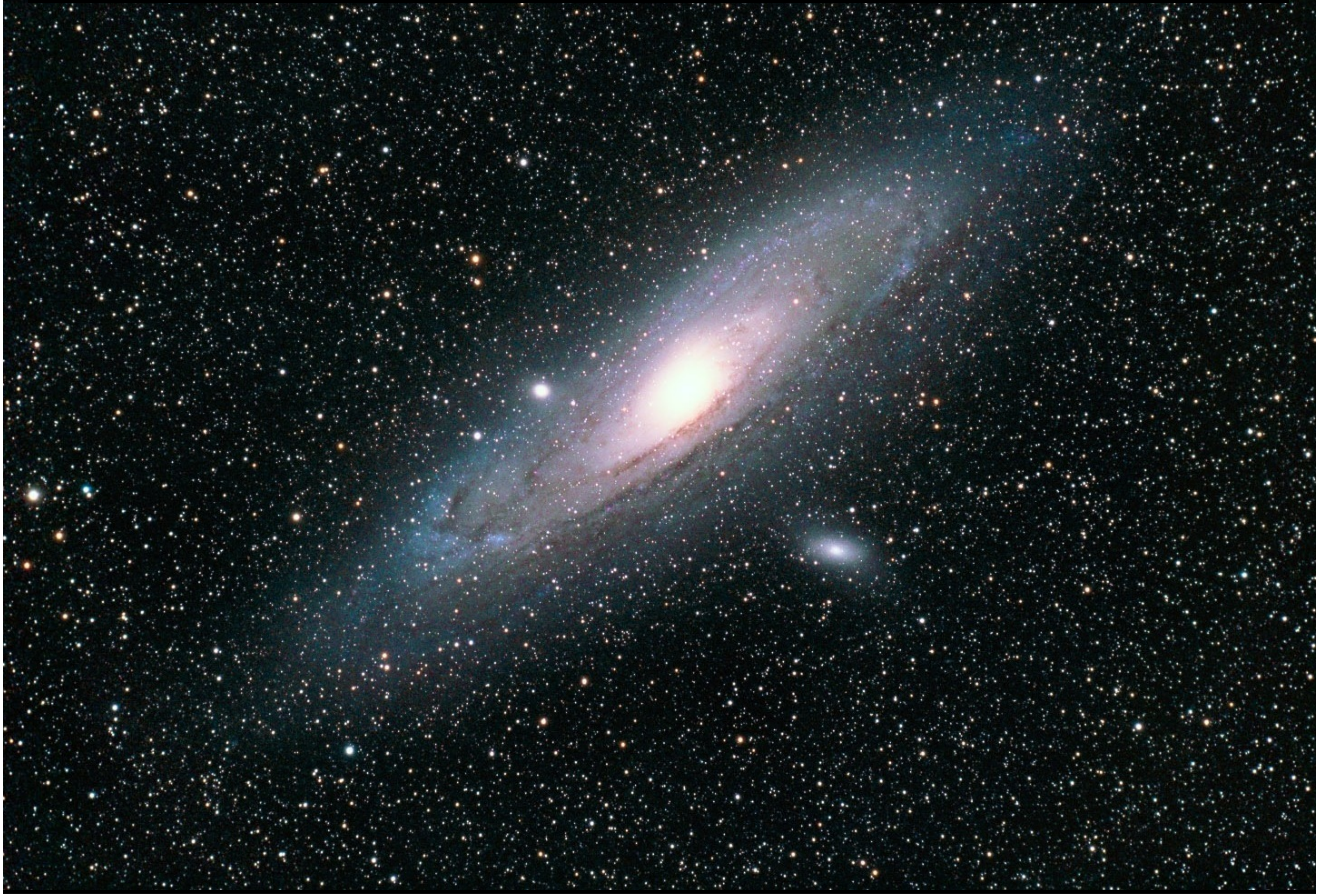
Typical mass of warm gas in CGM:
$M_{\text{Warm CGM}} \sim 2 \times 10^{10}\ M_\odot$

*There is probably not a galactic "missing baryons problem."*

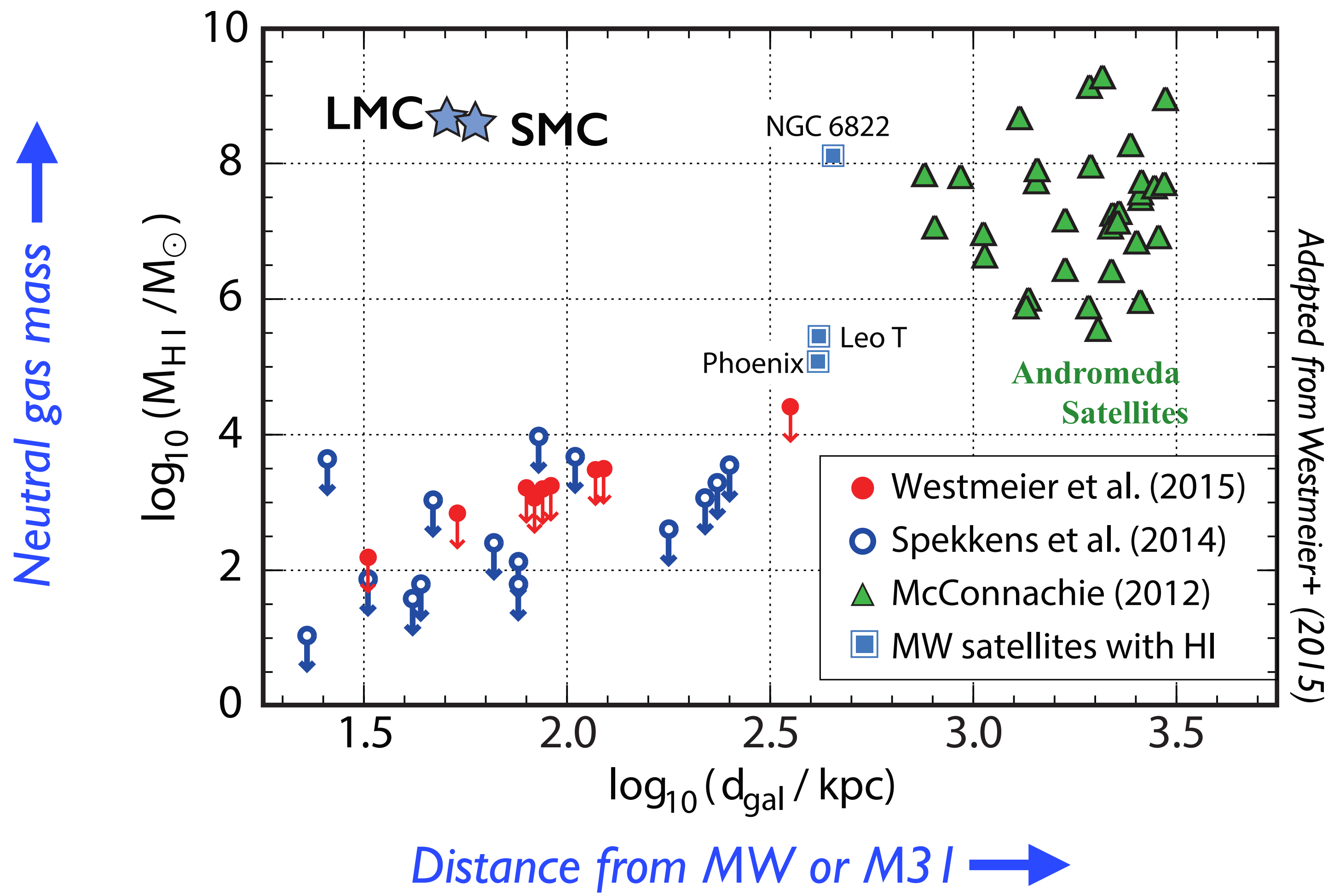
Estimated CGM mass in composite COS-Halos sample



# Local galaxies show CGM is a large baryon reservoir.

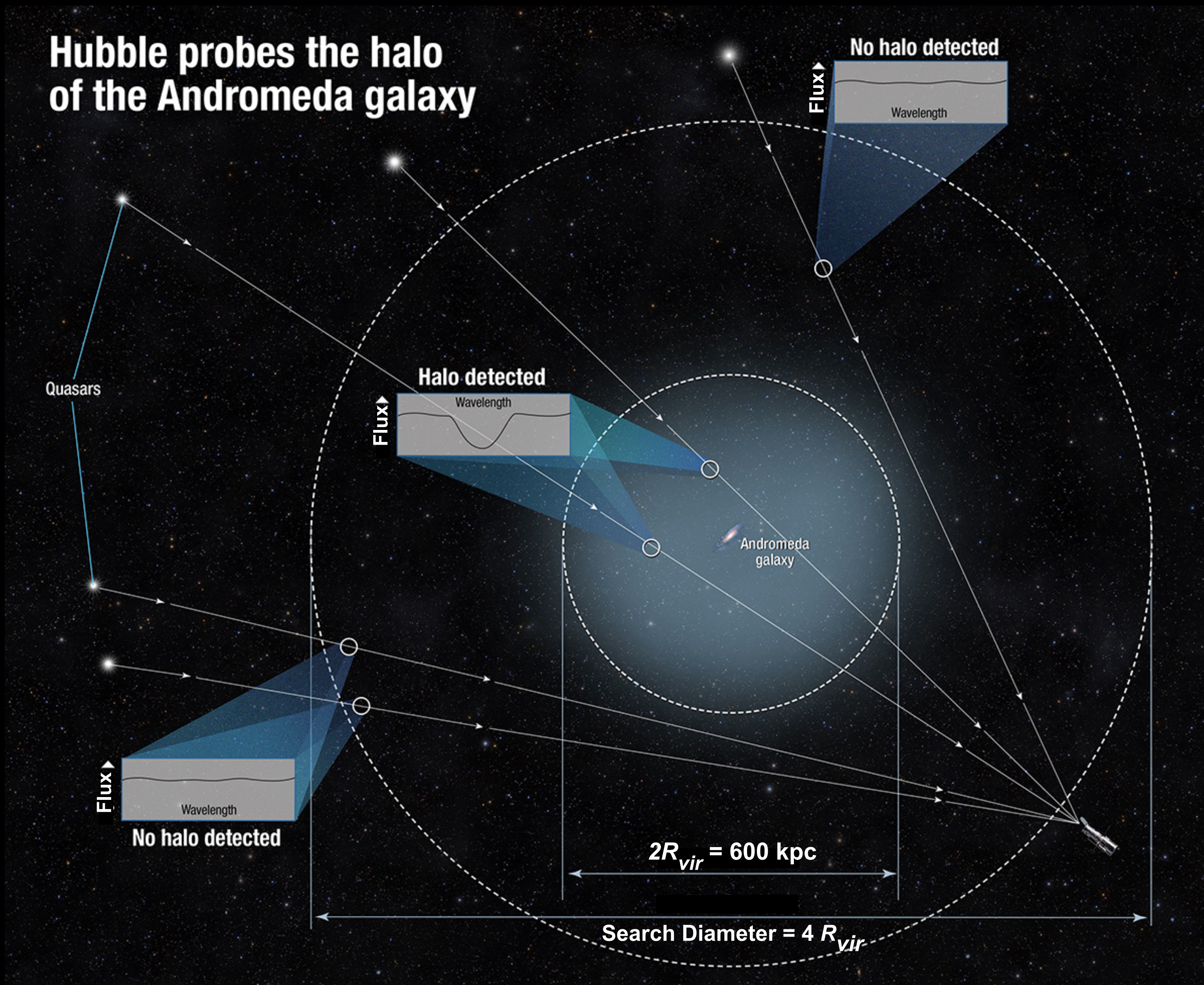


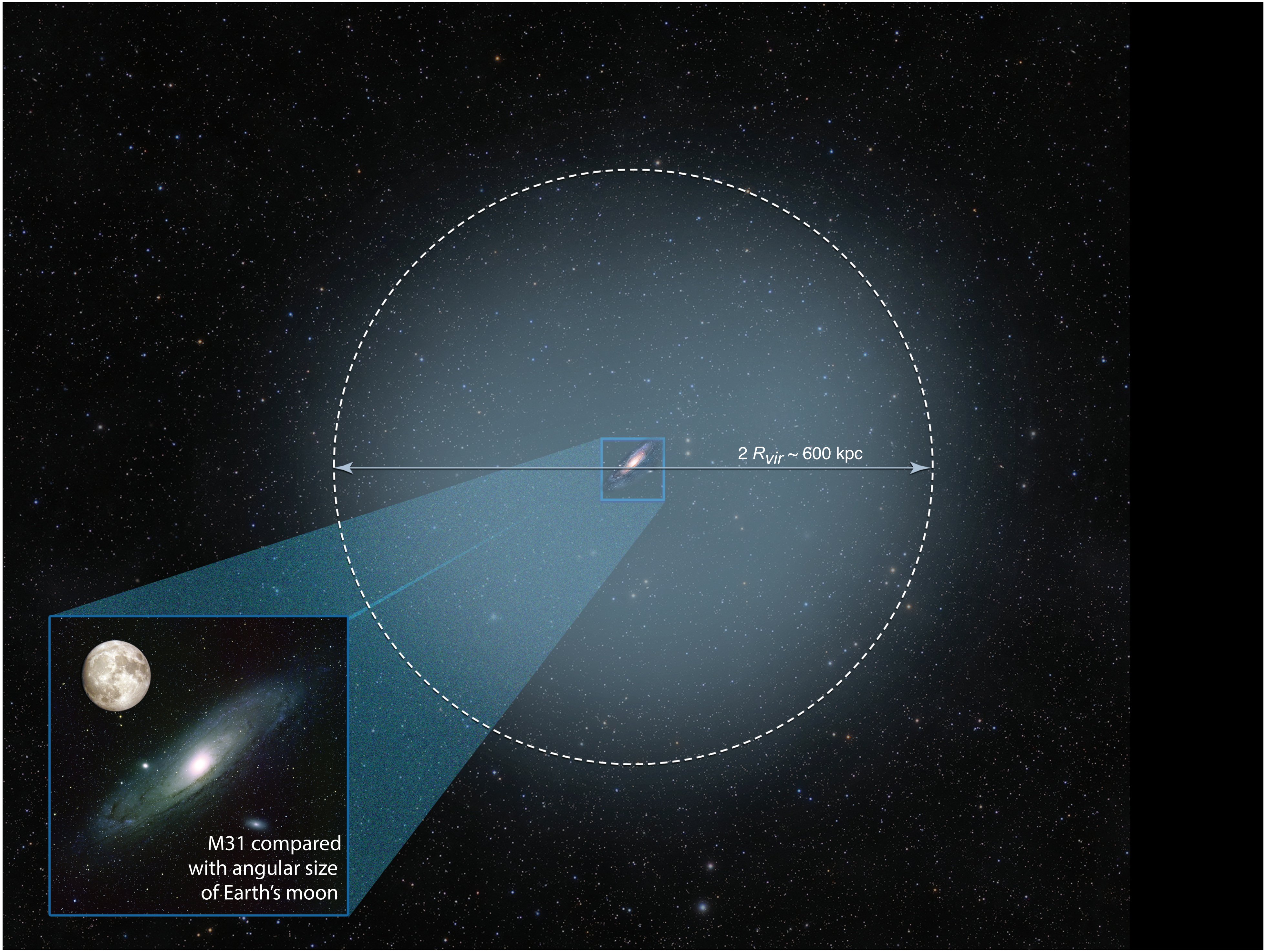
# Gas content of satellites hint at large gaseous halos about local galaxies.




*See also Grcevich & Putman (2009), Spekkens+ (2014)*

# Andromeda houses a huge gaseous halo.



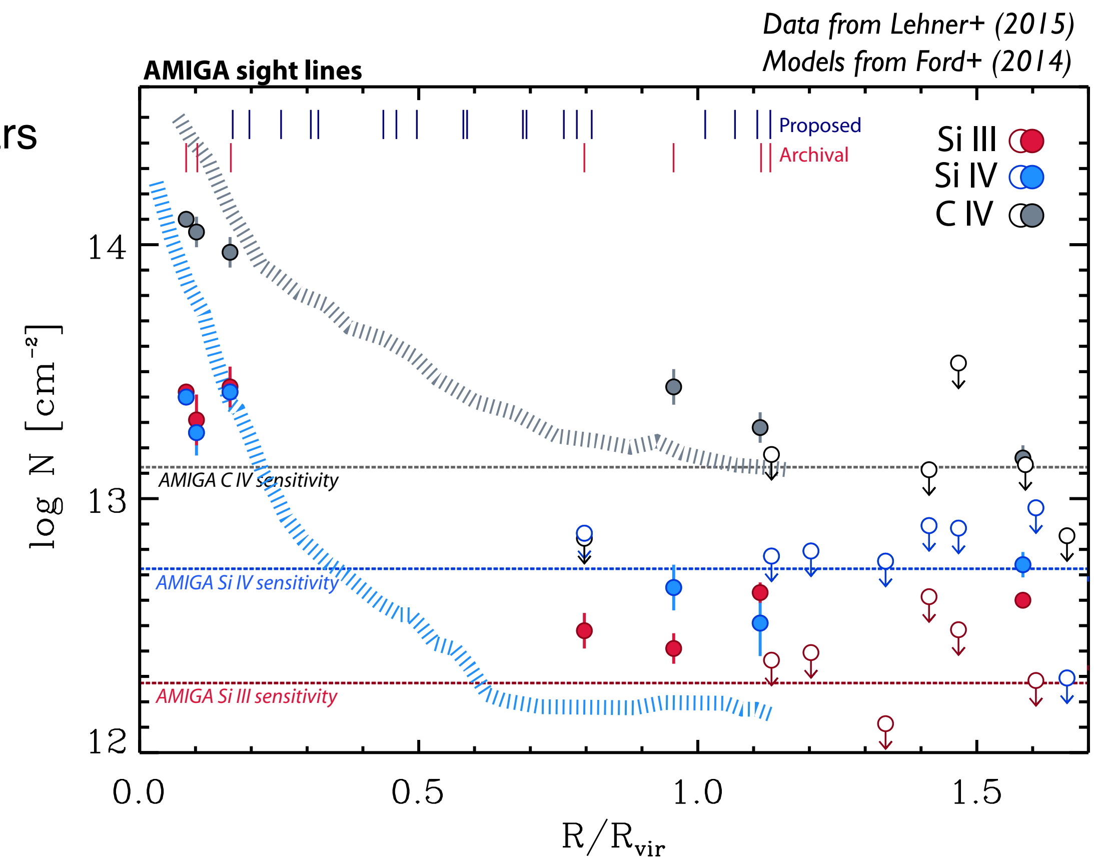

2 $R_{vir}$ ~ 600 kpc
M31 compared
with angular size
of Earth's moon

# Project AMIGA: Andromeda's CGM bears a large baryonic mass.

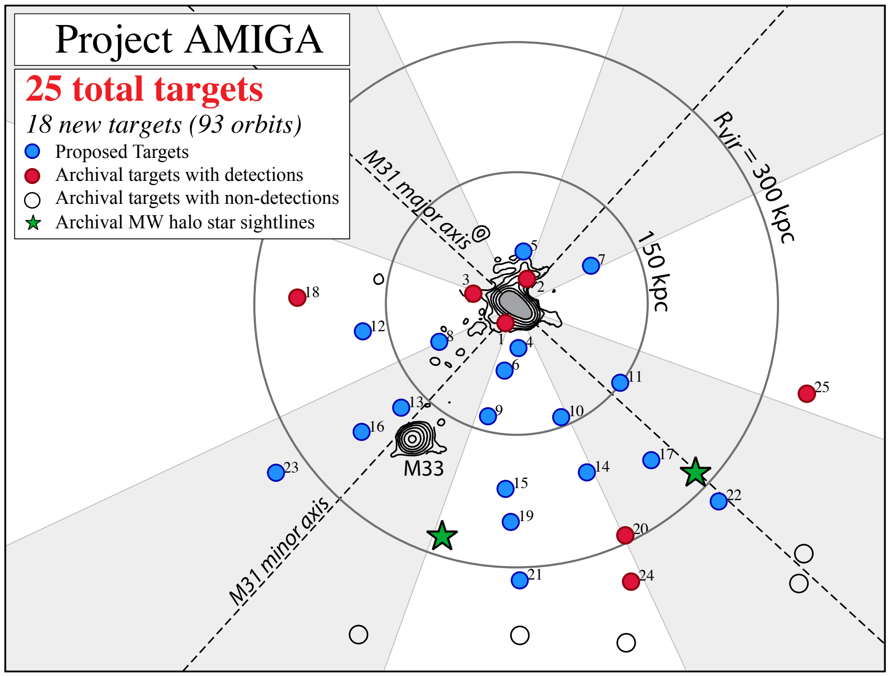
The CGM of the Andromeda galaxy bears at least ~10% of its stellar mass.

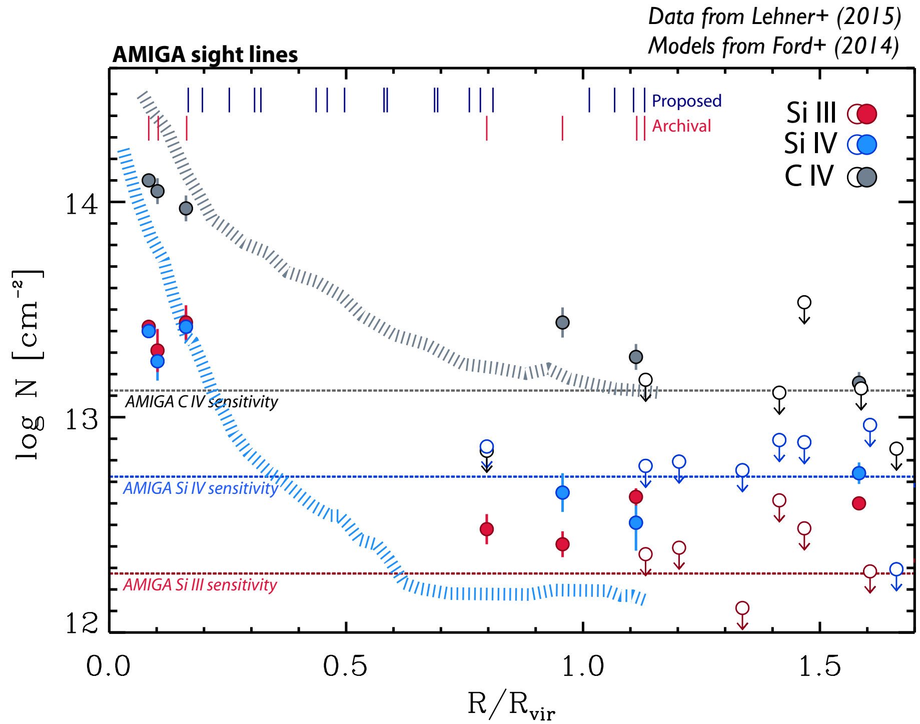
$M_{CGM}(\rho \leq 50 \text{ kpc}) > 3\text{x}10^{8}\ M_{\odot}$

$M_{CGM}(\rho \leq 300 \text{ kpc}) > 10^{9}\ M_{\odot}$

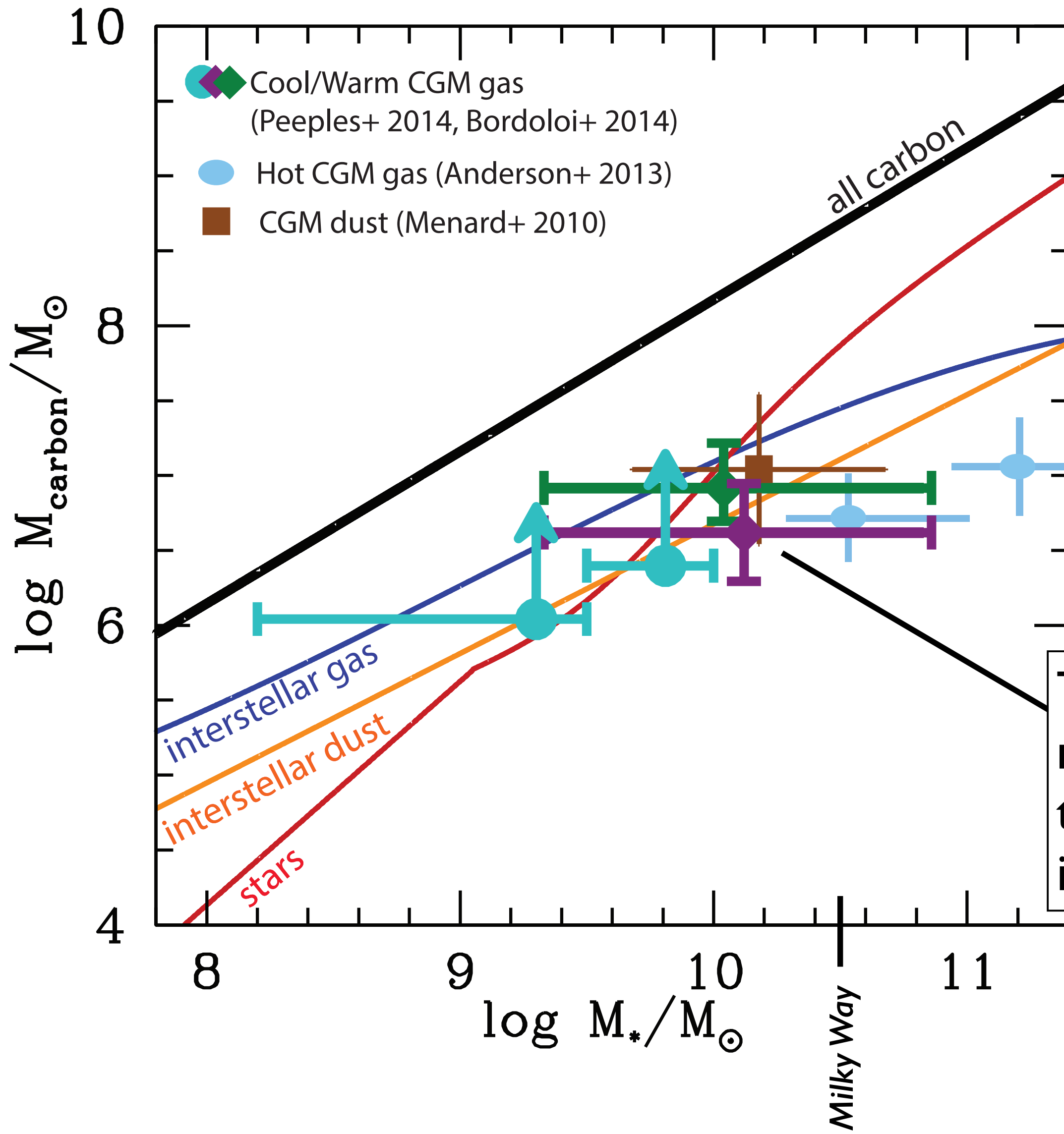


# Project AMIGA: Andromeda's CGM bears a huge baryonic mass.



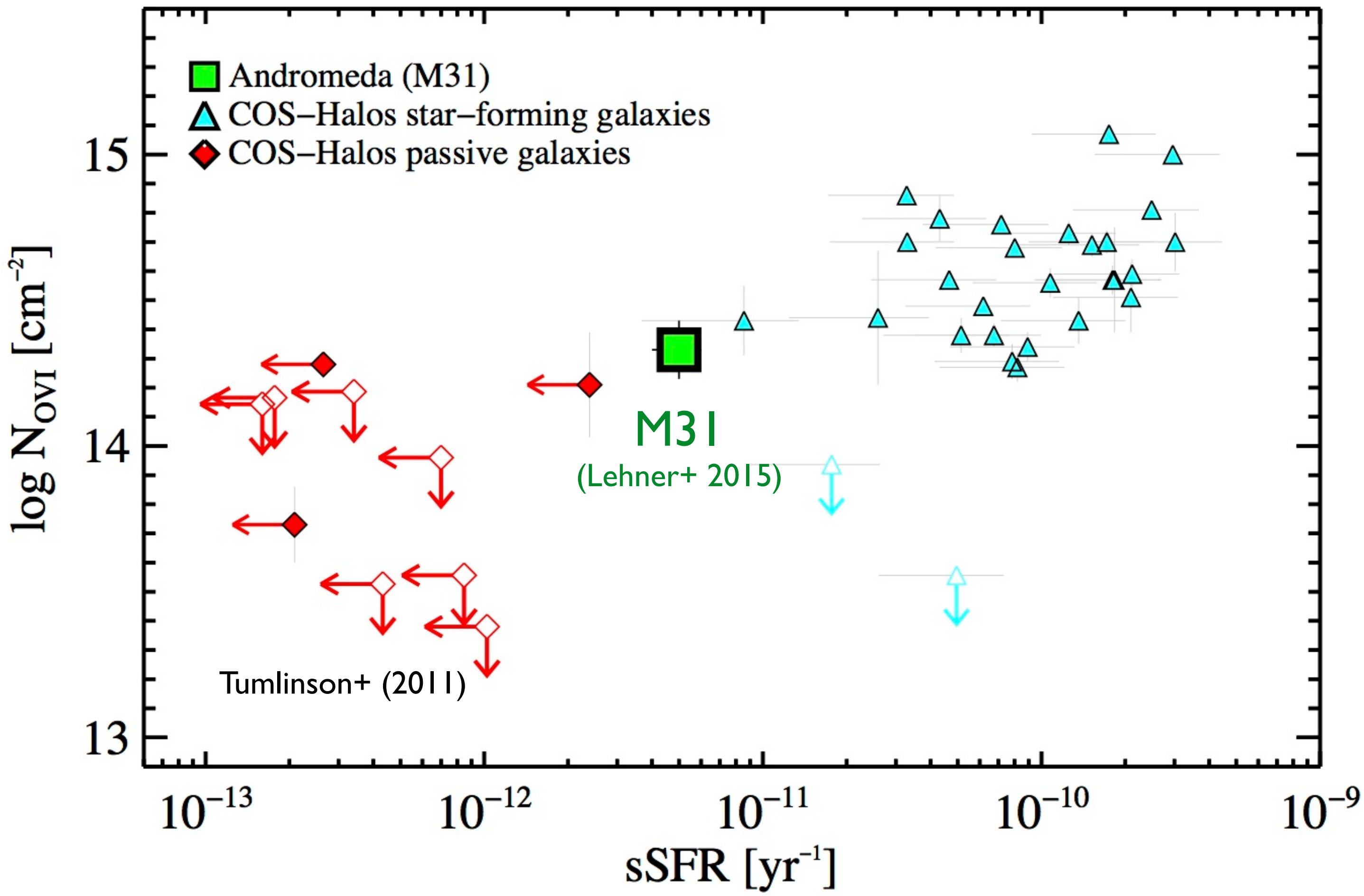
# The CGM harbors as many metals as stars in galaxies.




There are as many metals present in the CGM as in stars in galaxies.

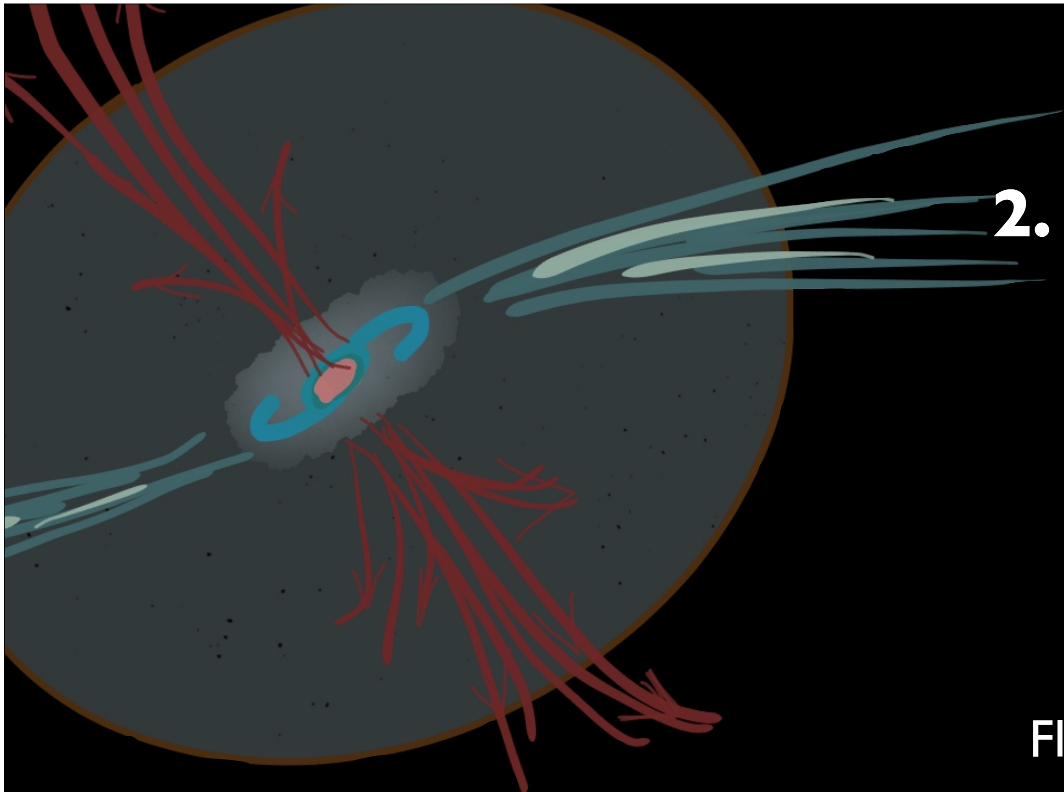
*First pointed out by Molly Peeples.*

# COS-Halos: warm metals in CGM associated with star formation.




The presence and quantity of "warm" metals is strongly correlated with star formation properties of galaxies.

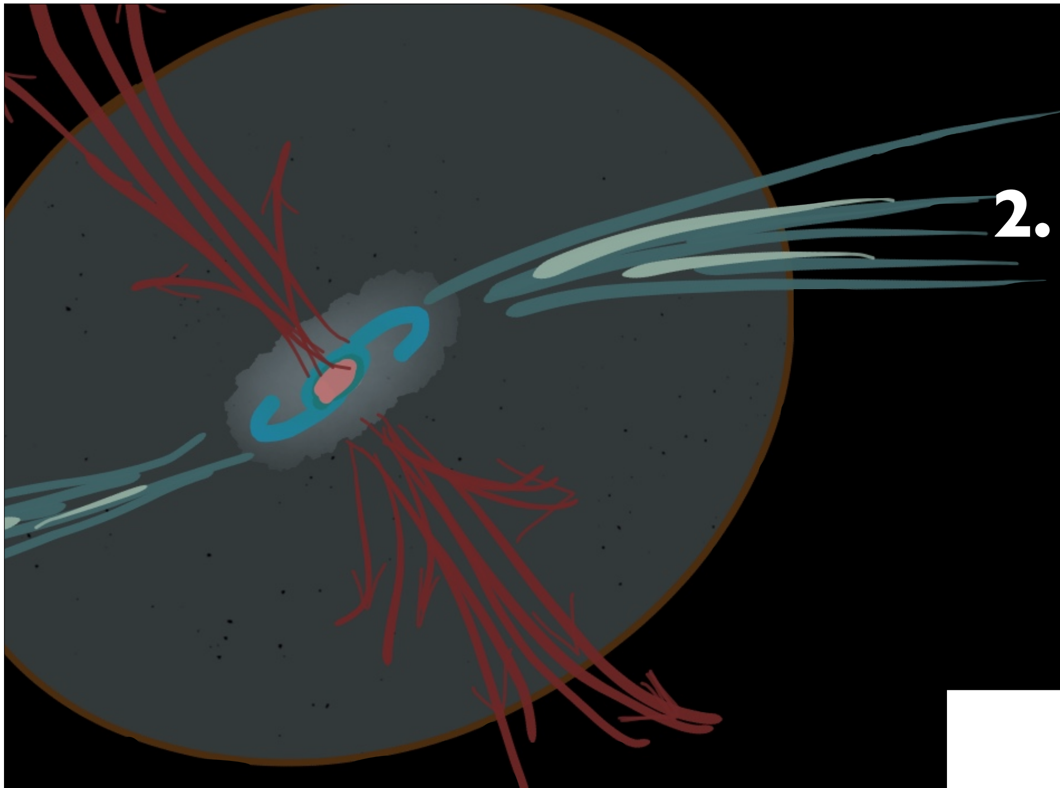
…but it is not for H I (Thom+ 2012).



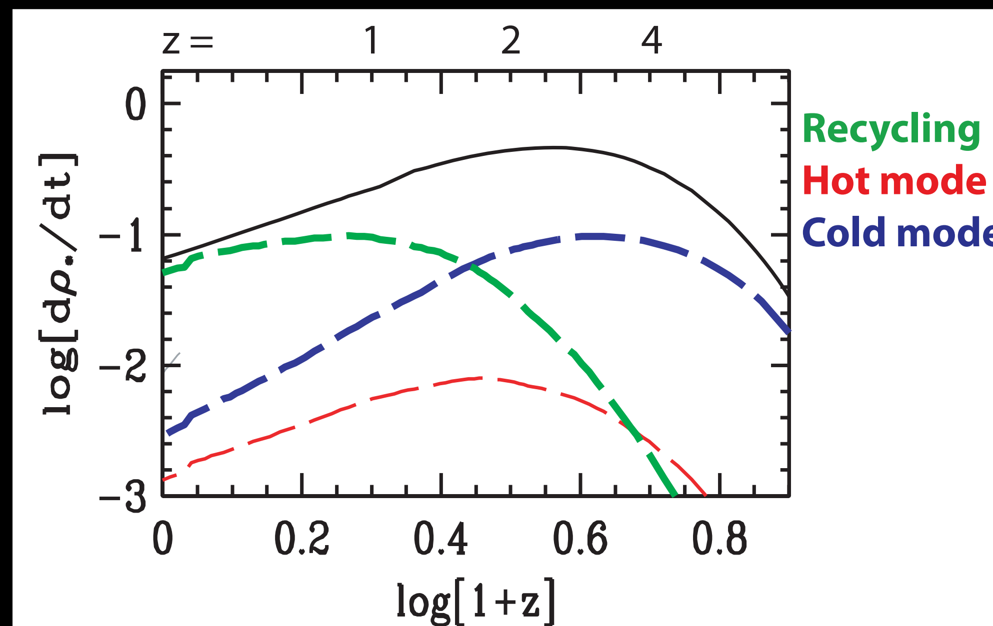
## 2. What role does the CGM play in shaping galaxies?

Flows through the CGM or condensation out of CGM gas provides fuel for star formation in galaxies.

## 2. What role does the CGM play in shaping galaxies?



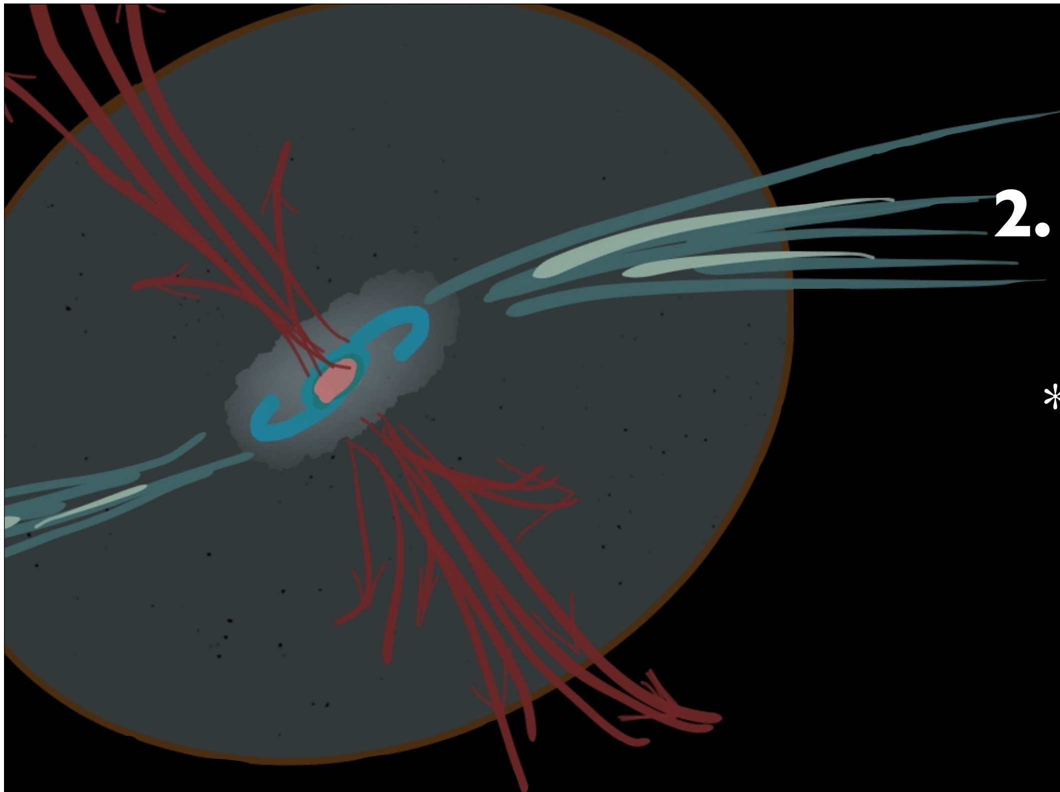
*A majority of stars in z=0 galaxies may have been formed by “recycled” CGM gas (winds).

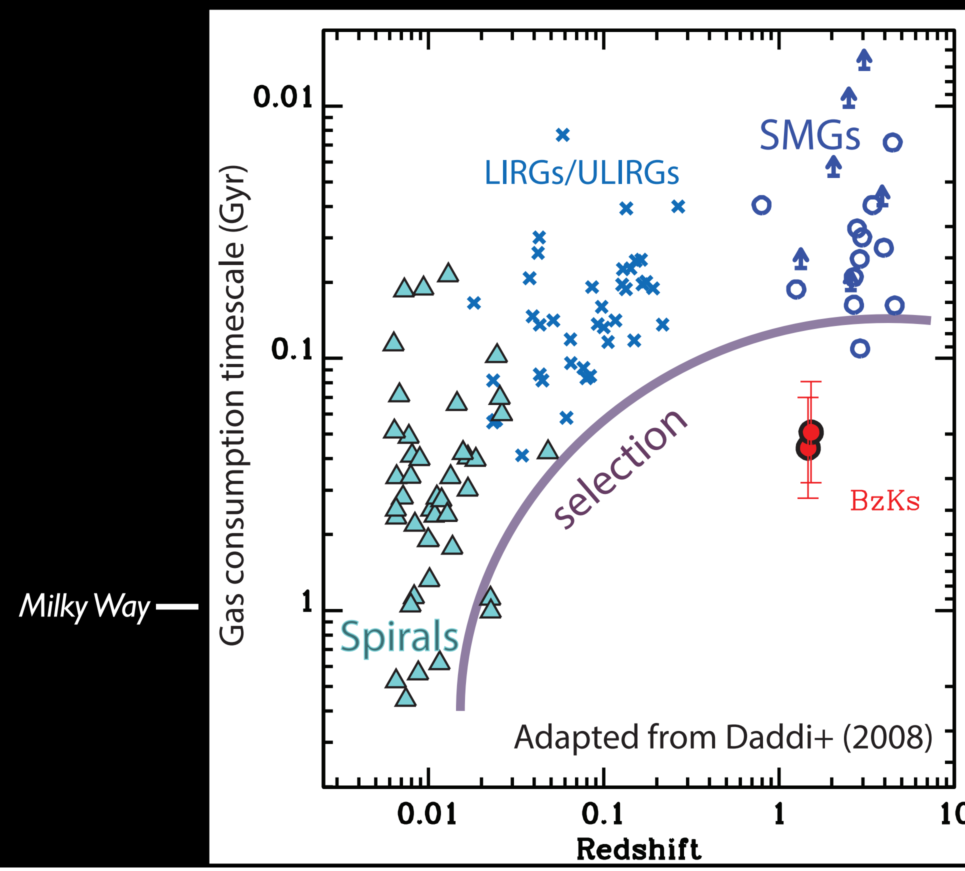


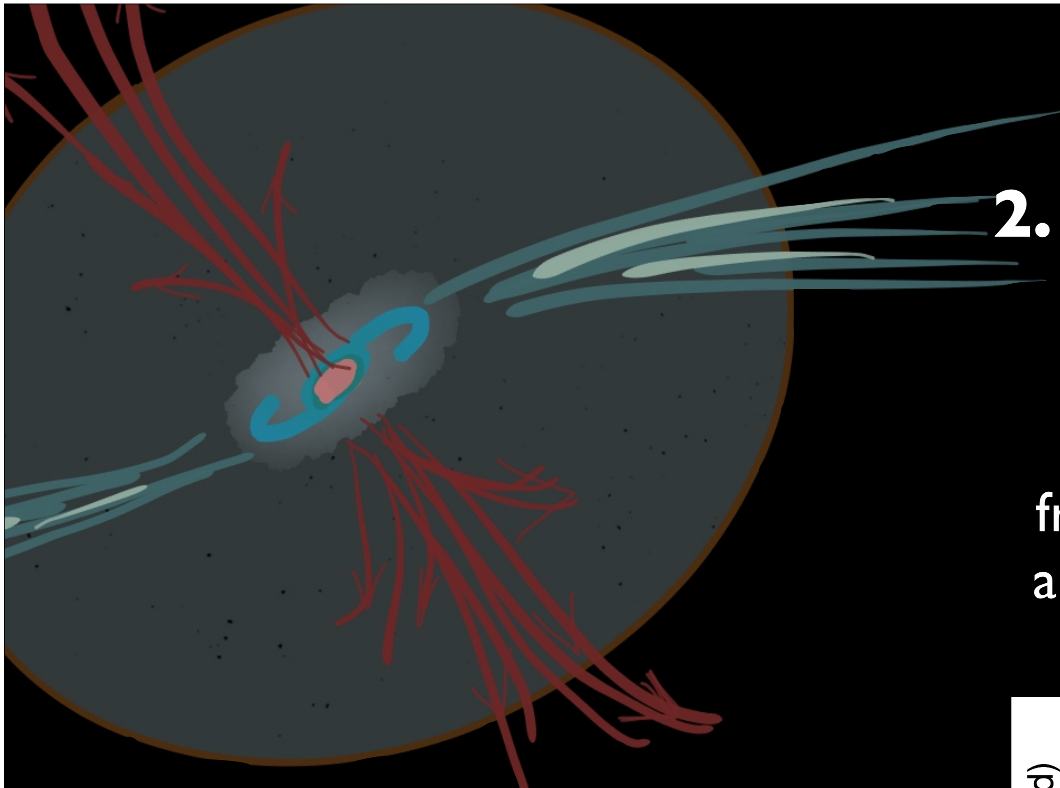

Oppenheimer+ (2010)

# 2. What role does the CGM play in shaping galaxies?

*Infall of metal-poor IGM gas may be required to fuel multi-Gyr star formation in galaxies.

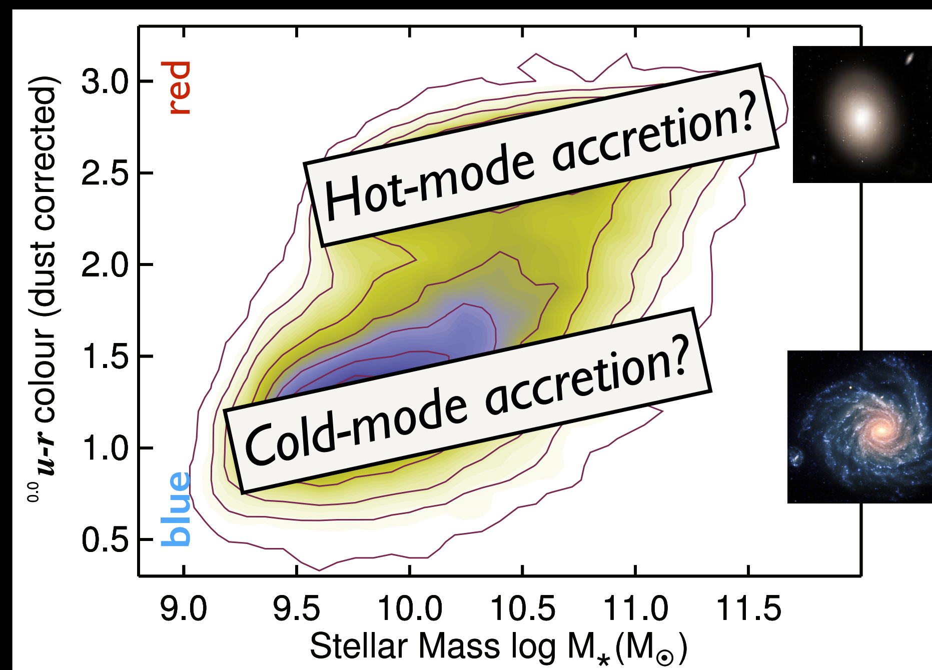






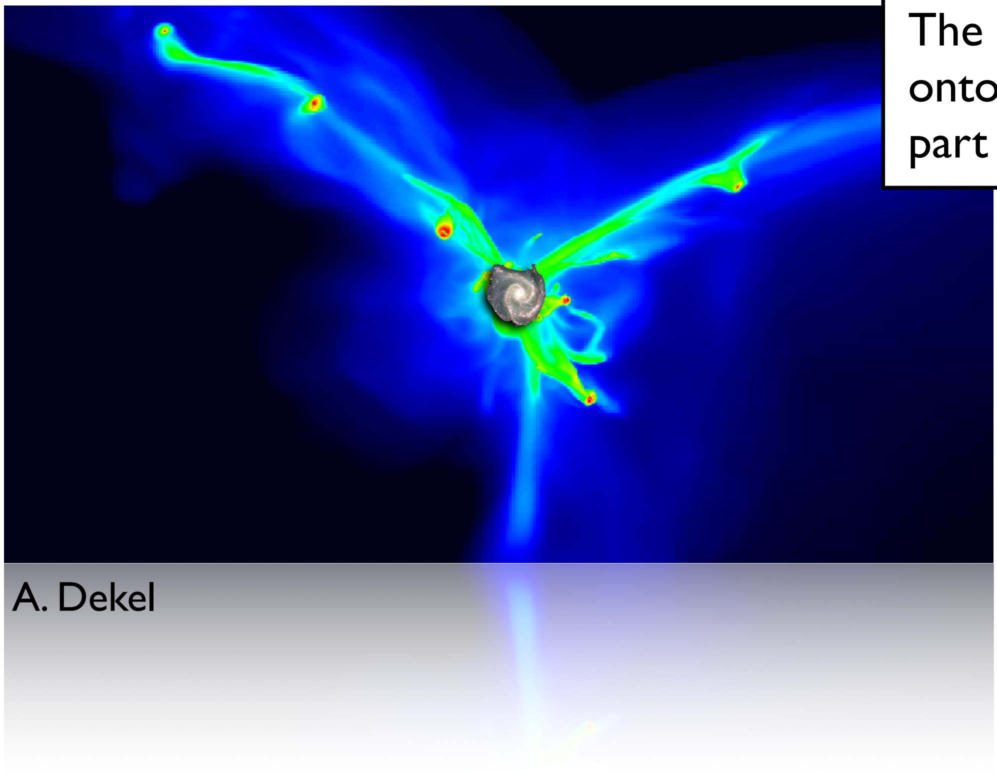
# 2. What role does the CGM play in shaping galaxies?

*The CGM may keep incoming fuel from reaching the centers of galaxies, and thus in quenching star formation.




Schawinski+ (2014)

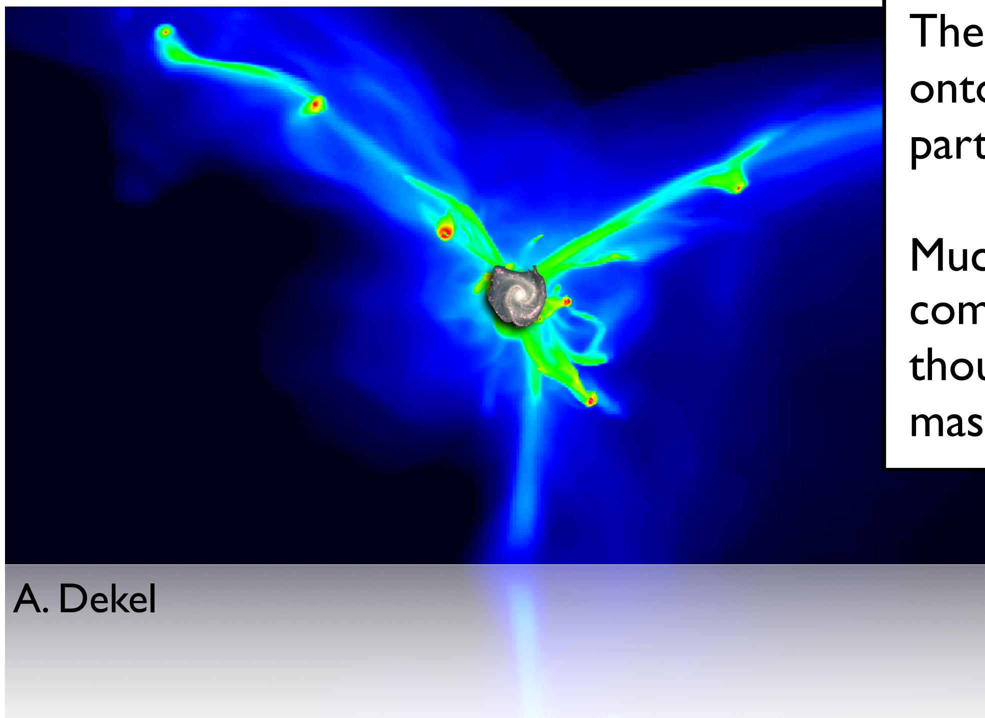
# Cold Gas Accretion onto Galaxies



A. Dekel

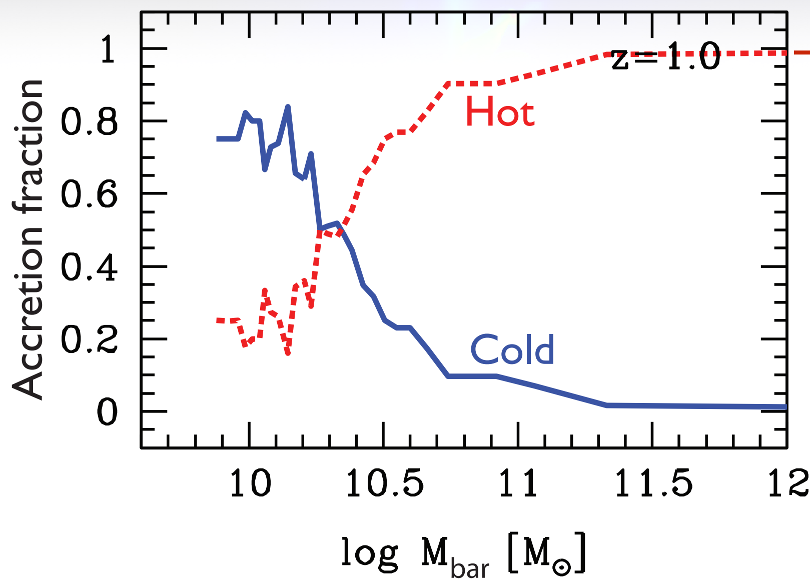
The ***accretion** of IGM gas* onto galaxies is a crucial part of their evolution.

# Cold Gas Accretion onto Galaxies




The ***accretion*** *of IGM gas* onto galaxies is a crucial part of their evolution.

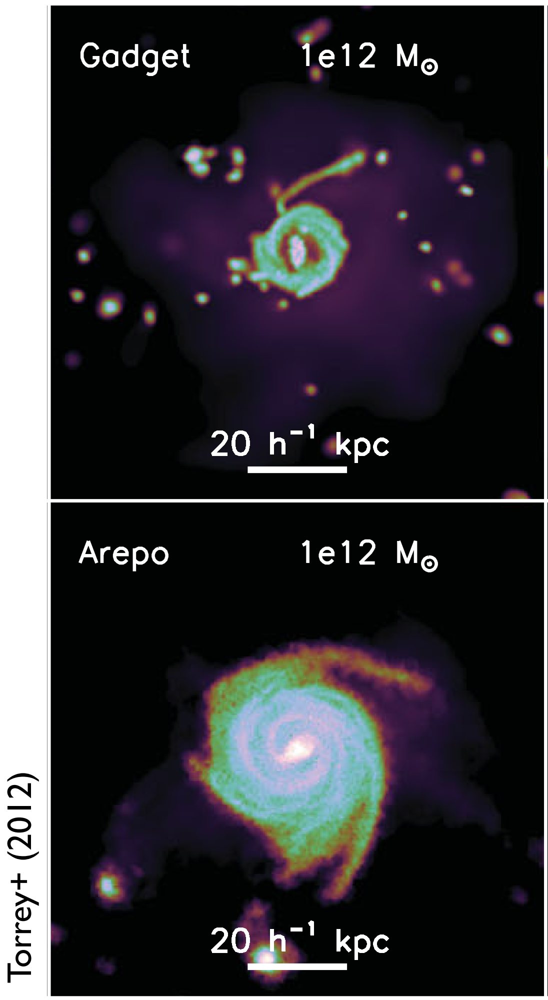
Much of this matter may come in "cold," but this is thought to depend on the mass of the central galaxy.

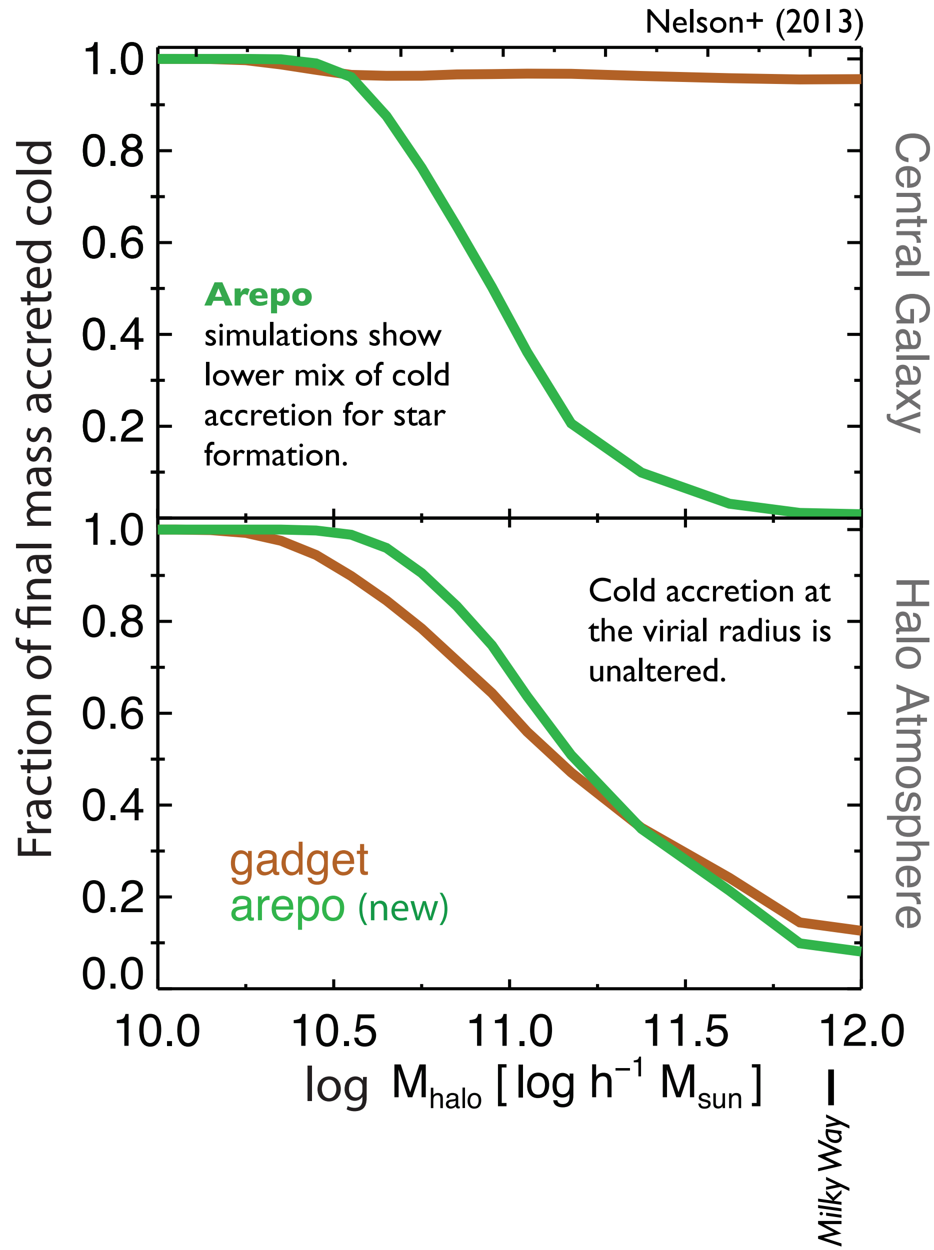



*Shock heated by hot CGM, not readily available for SF.*

Keres+ (2005)

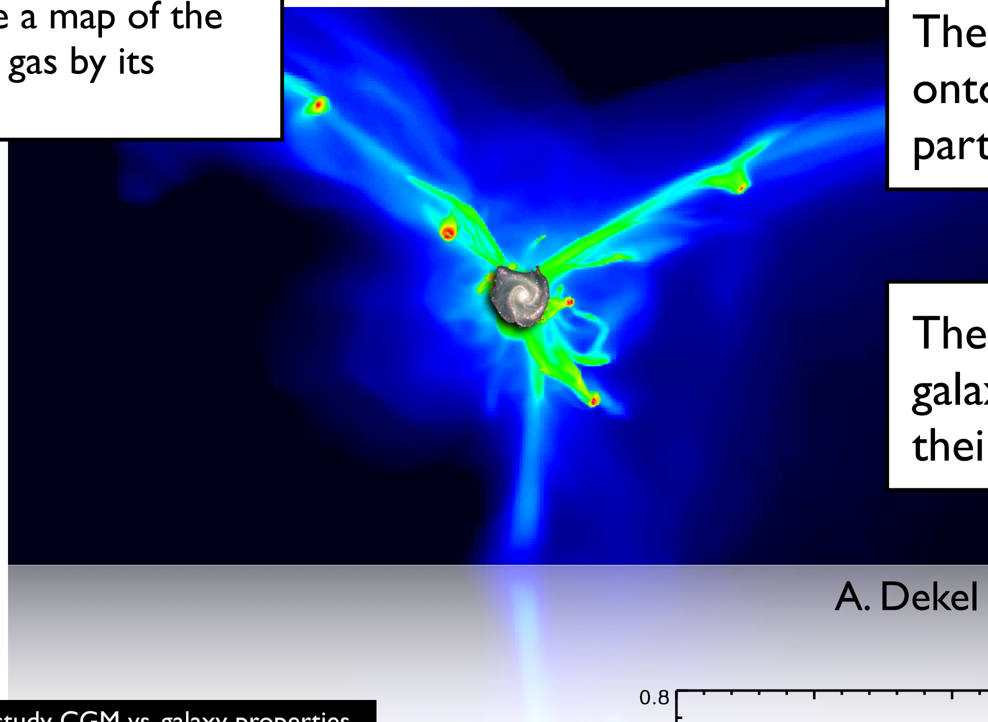
# Role of cold accretion is topic of hot debate.



# We want to dissect the CGM of galaxies, learning about each component.

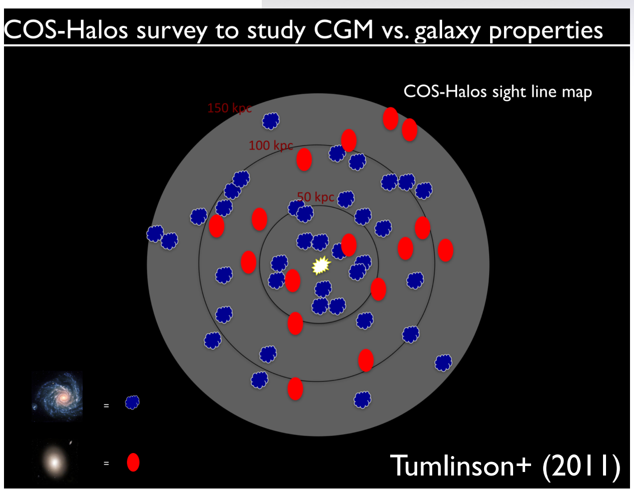
We'd like to make a map of the CGM and tag the gas by its origins.

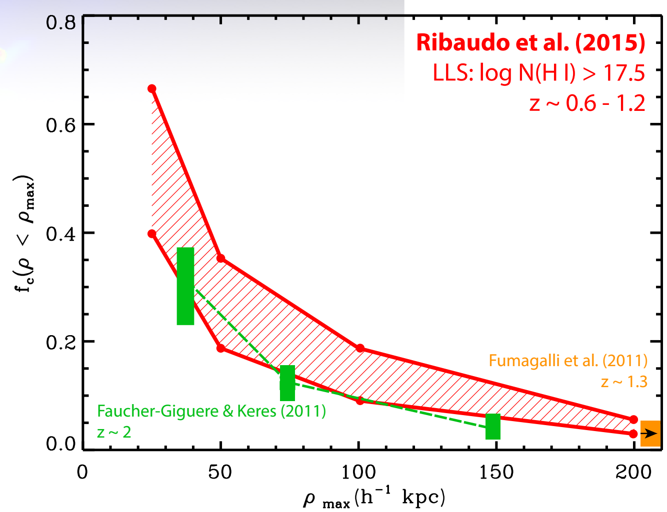


A. Dekel

The ***accretion of IGM gas*** onto galaxies is a crucial part of their evolution.

The ***expulsion of gas*** from galaxies is a crucial part of their evolution.

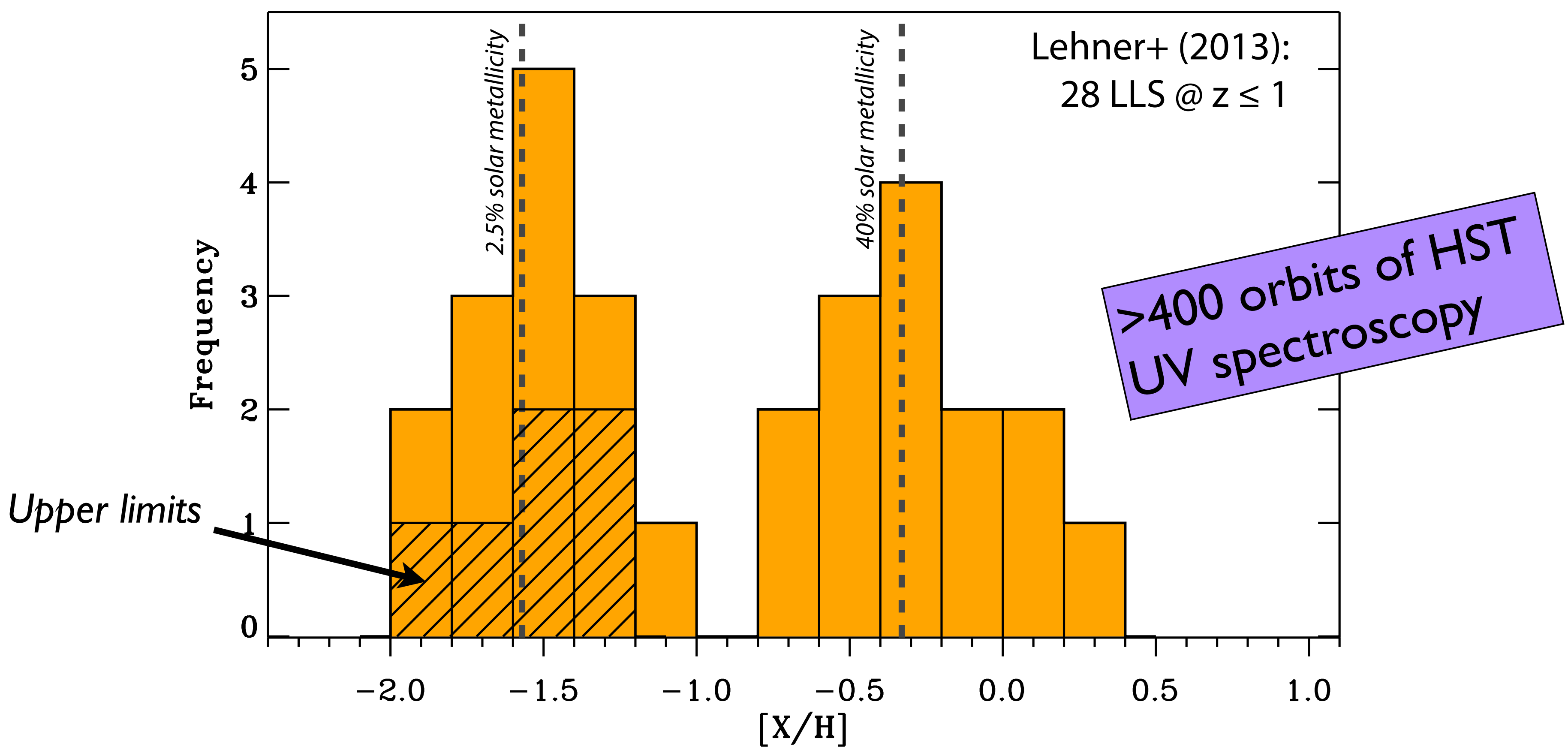



COS-Halos attempts this…but the covering factors of streams are small!

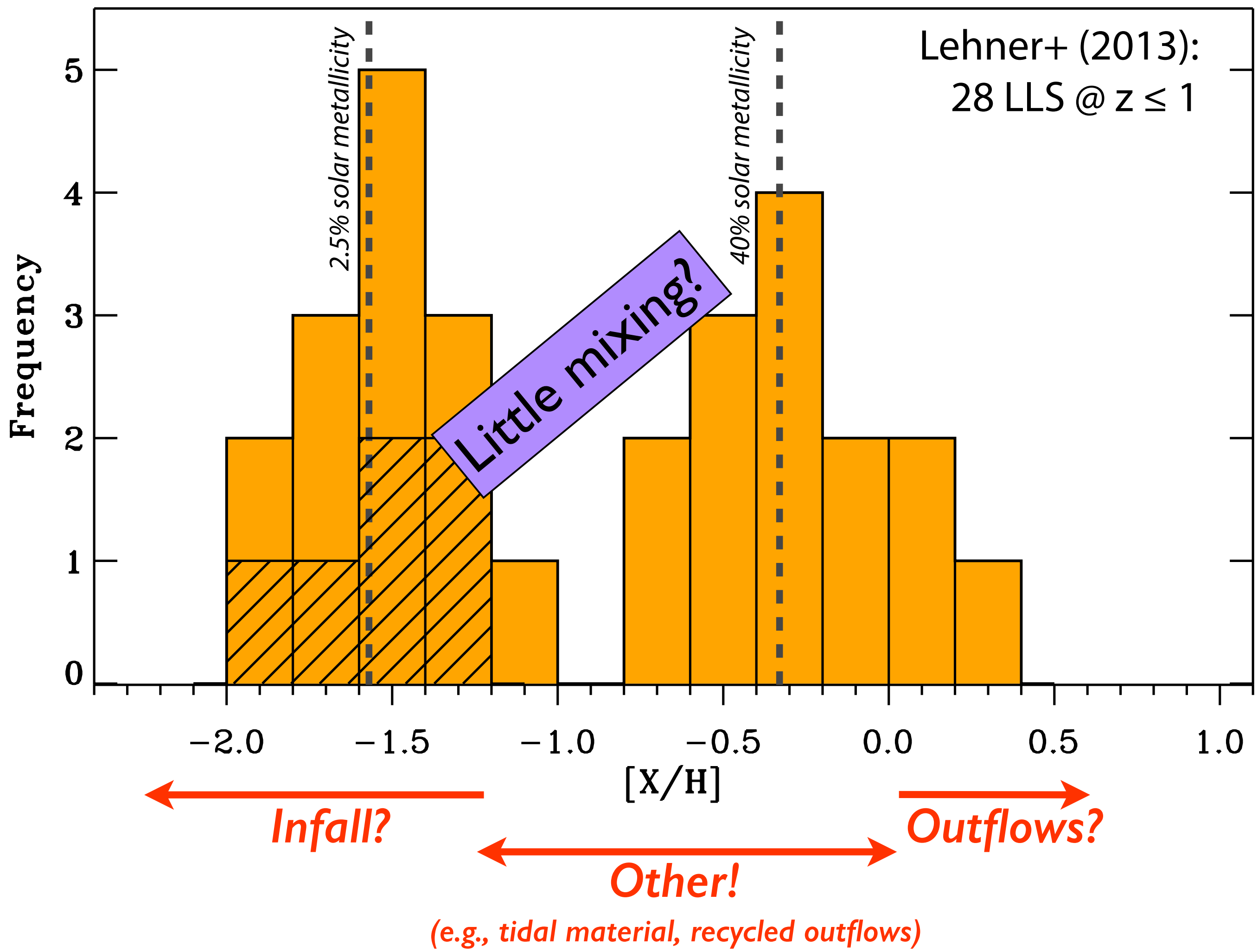
# Lyman limit systems probe infall and outflows at low-z.

Metallicity distribution of z ≤ 1.0 Lyman limit systems
[16.1 ≤ log N(H I) ≤ 18.5]



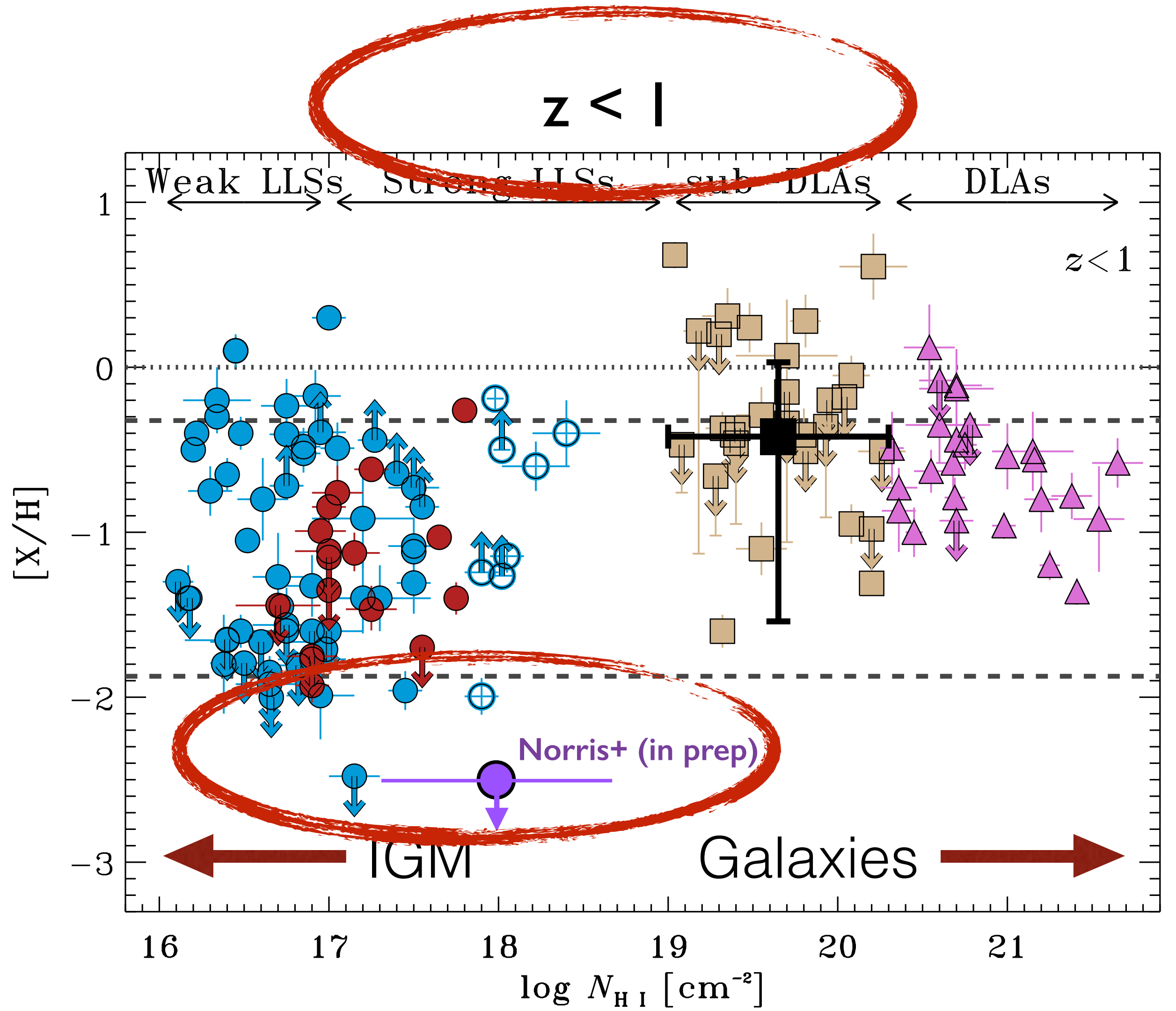
# Lyman limit systems probe infall and outflows at low-z.

Metallicity distribution of z ≤ 1.0 Lyman limit systems
[16.1 ≤ log N(H I) ≤ 18.5]




Lehner+ (2013)

# Surprises still to be found




Wotta+ (2017)



***I like it!***

J. Christopher Howk
*U. Notre Dame / U. Católica*


# LUVOIR: $D_A \sim 15$ m

*UV spectroscopy:*

$\lambda_{UV}$ ~1,000 – 4,000 Å

$R$ ~ 500; 5,000; **50,000** **...500,000?**

MOS/IFU over ~2′ field.

What cool things can we do with LUVOIR?

What do we need to get ready for and scope the design requirements of LUVOIR?

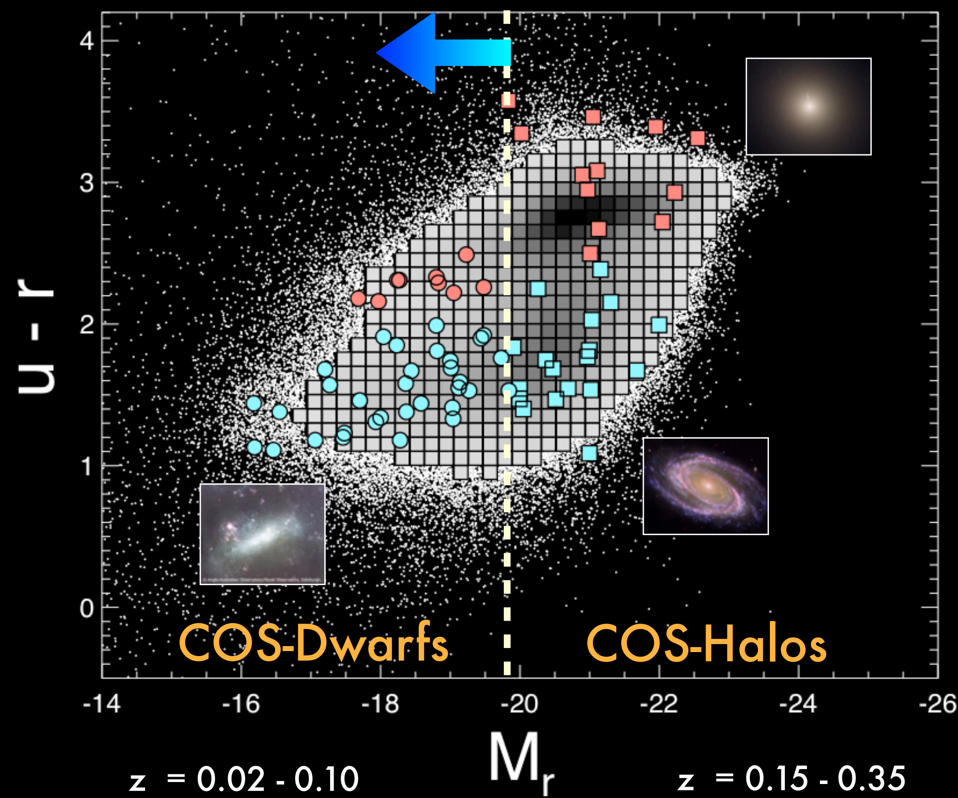
What legacy do we want to leave for our decade without UV access?

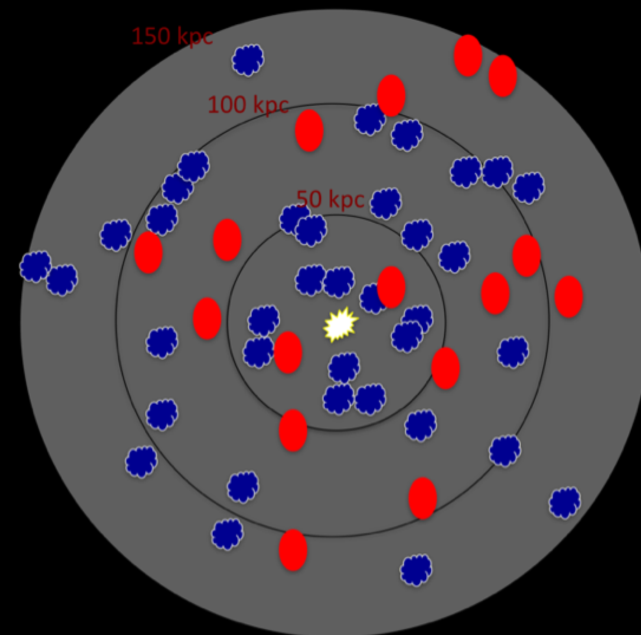
# LUVOIR will not be just HST with a bigger aperture

*What doesn't HST do well?*

- High-resolution spectroscopy at high sensitivity
- FUV (<1200 Å)
- NUV (>1800 Å)
- Multiplexed spectroscopy

- Simulations (!)



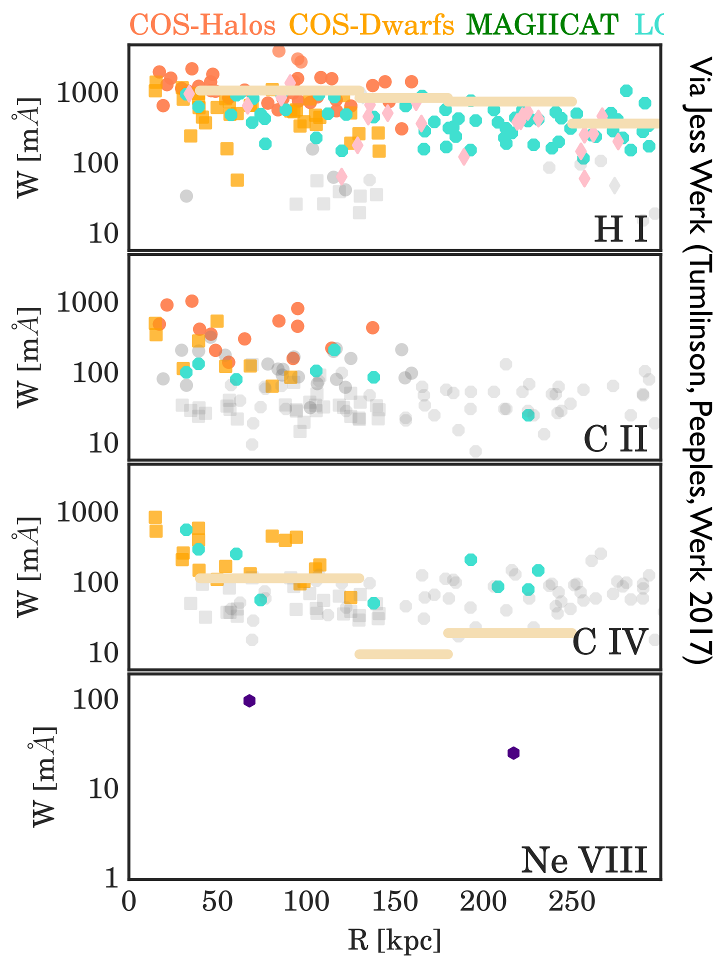



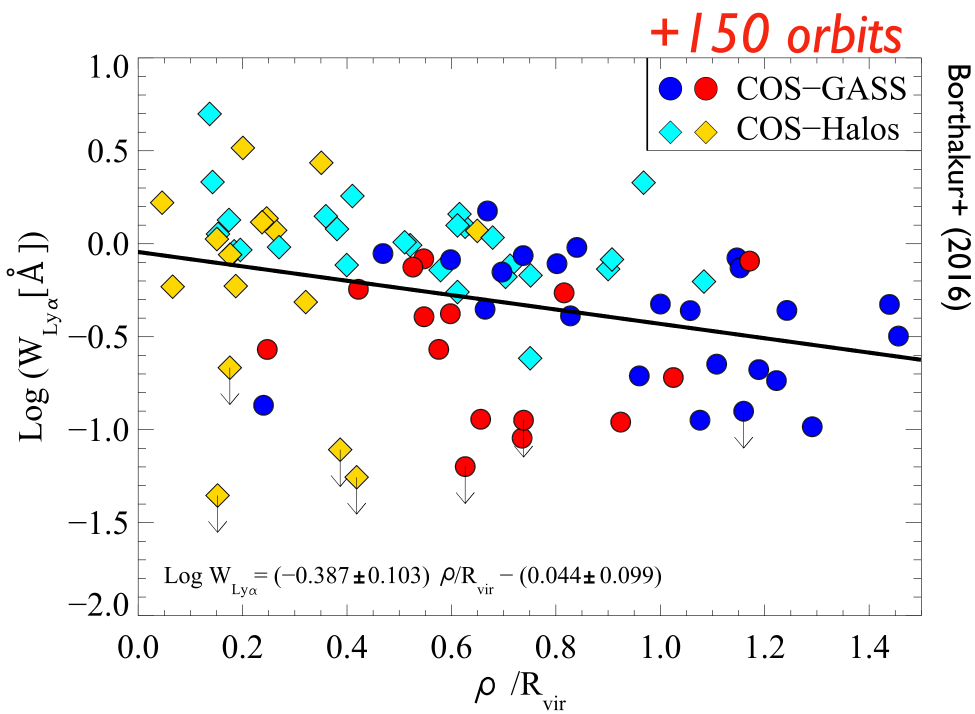

z = 0.02 - 0.10
logM* = 8 - 10
optimal for CIV

z = 0.15 - 0.35
logM* = 10 - 11.5
optimal for OVI

*These 2 HST programs represent ~300 HST orbits.*

# We use EW measurements, harkening back to **Strömgren**??



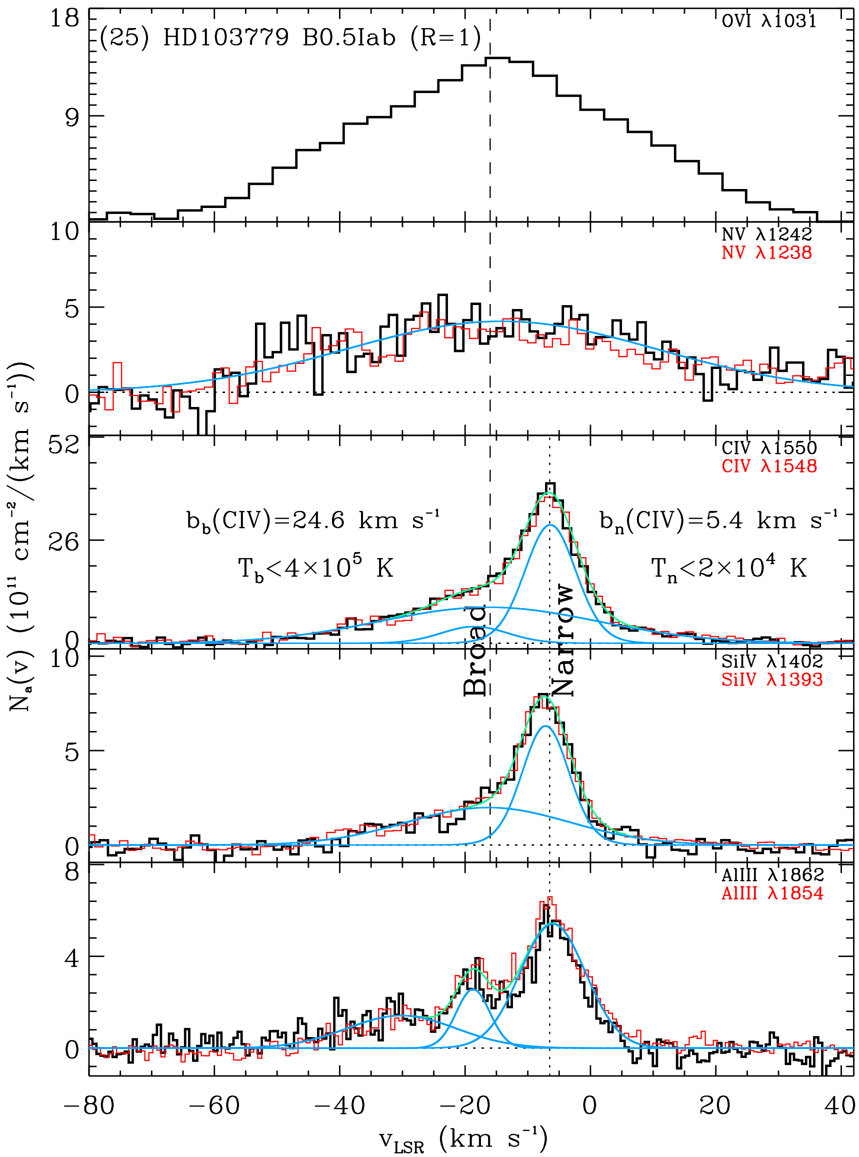

*The EW does not tell us how much gas is there (necessarily). It is a complex combination of the surface density of gas, the temperature and turbulence within that gas, and the overlap of gaseous structures.*

## Why do we still do this?

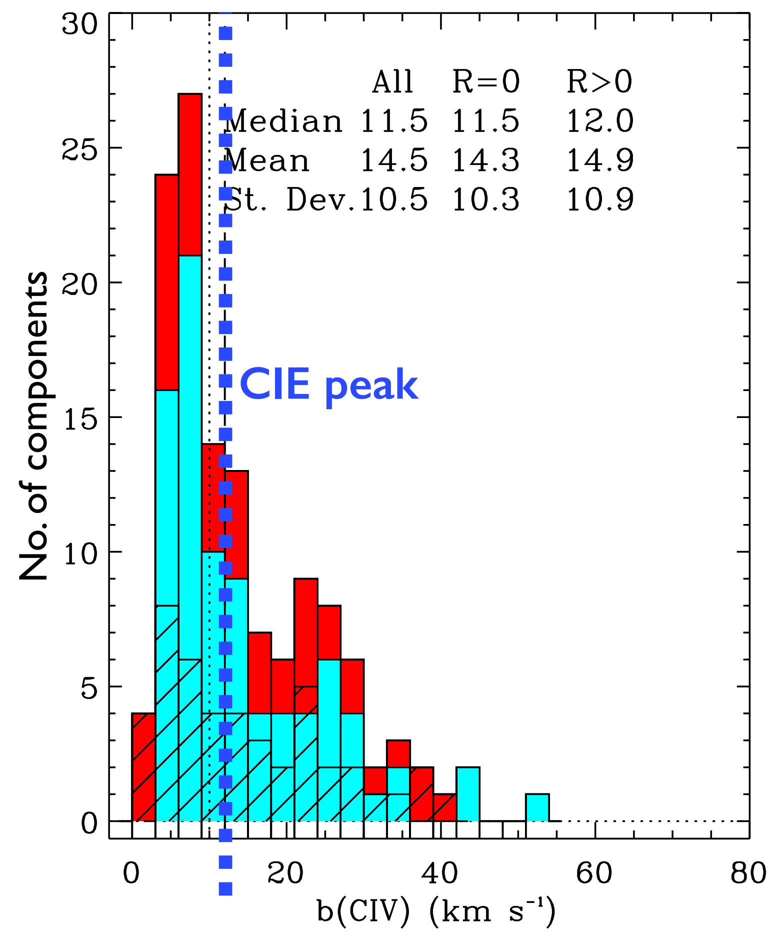
*We have no choice:*

Resolution, wavelength coverage, S/N limit our ability to derive column densities.

# Resolution, S/N matter

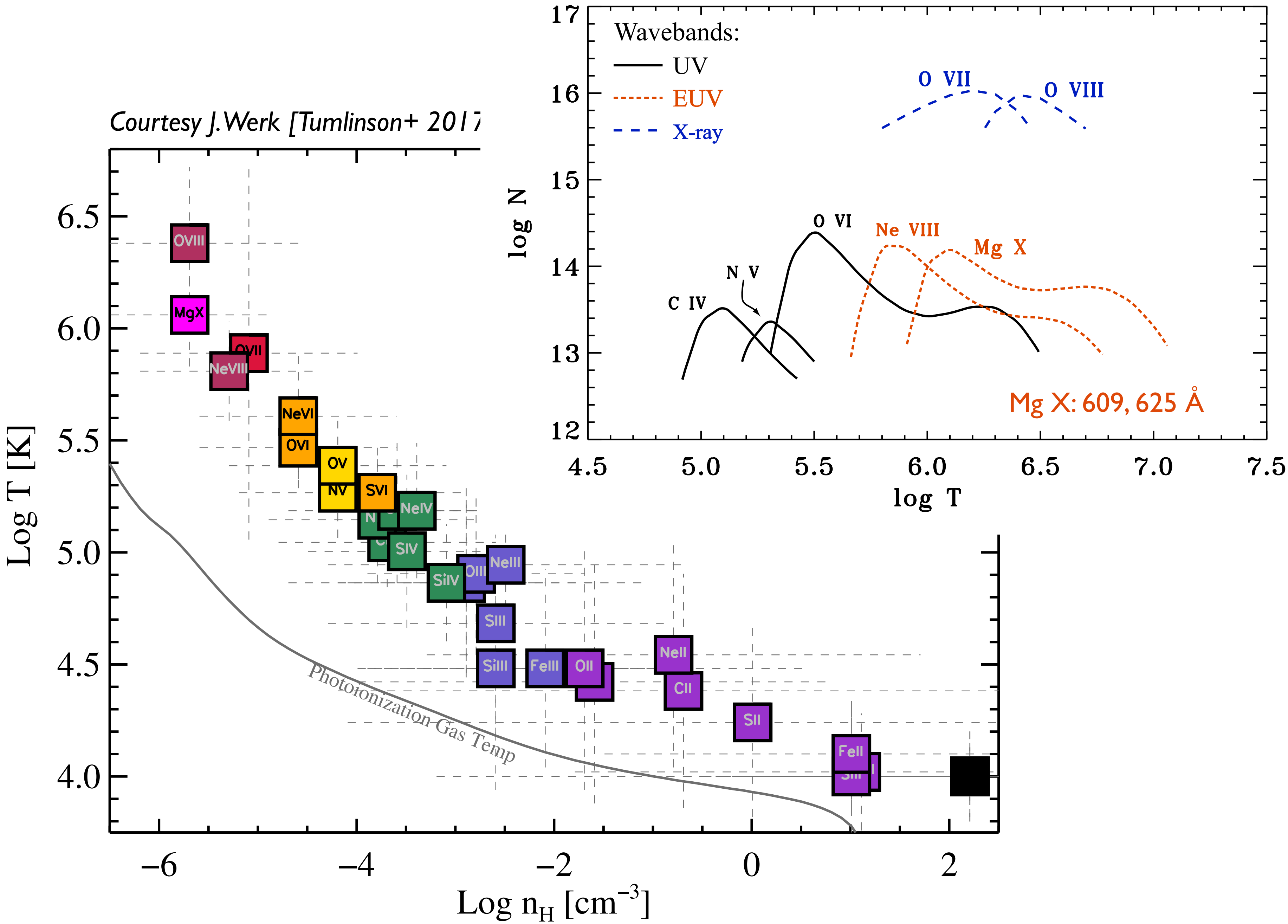



***The more limitations we have on spectroscopy, the further we get from the physics.***

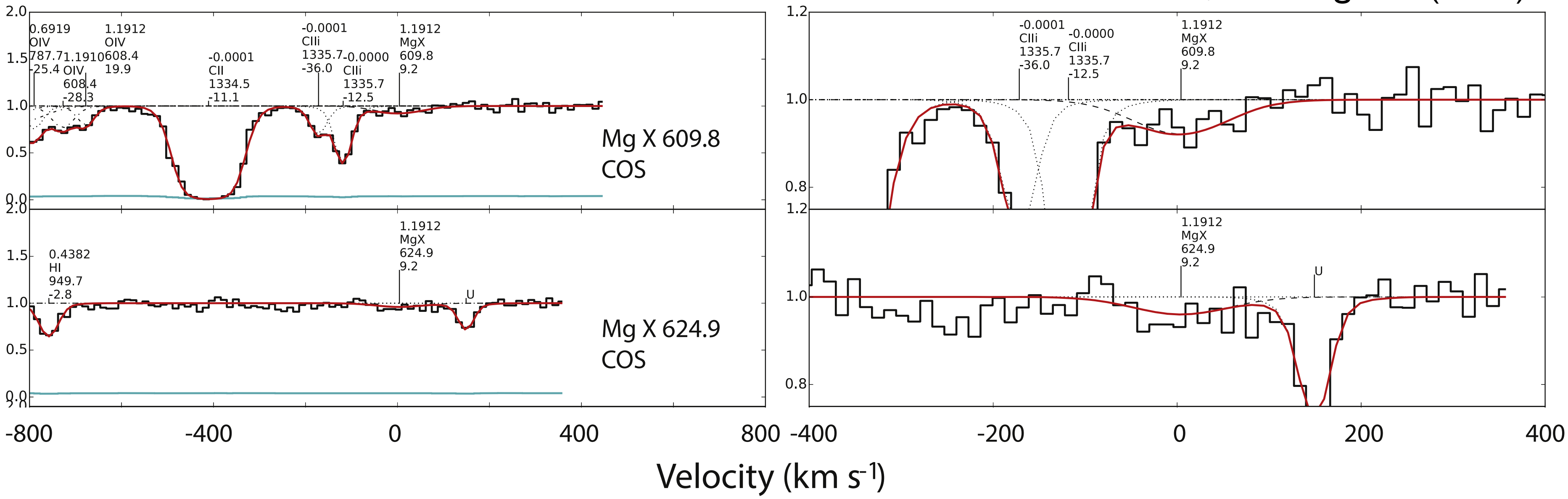



Lehner+ (2011)

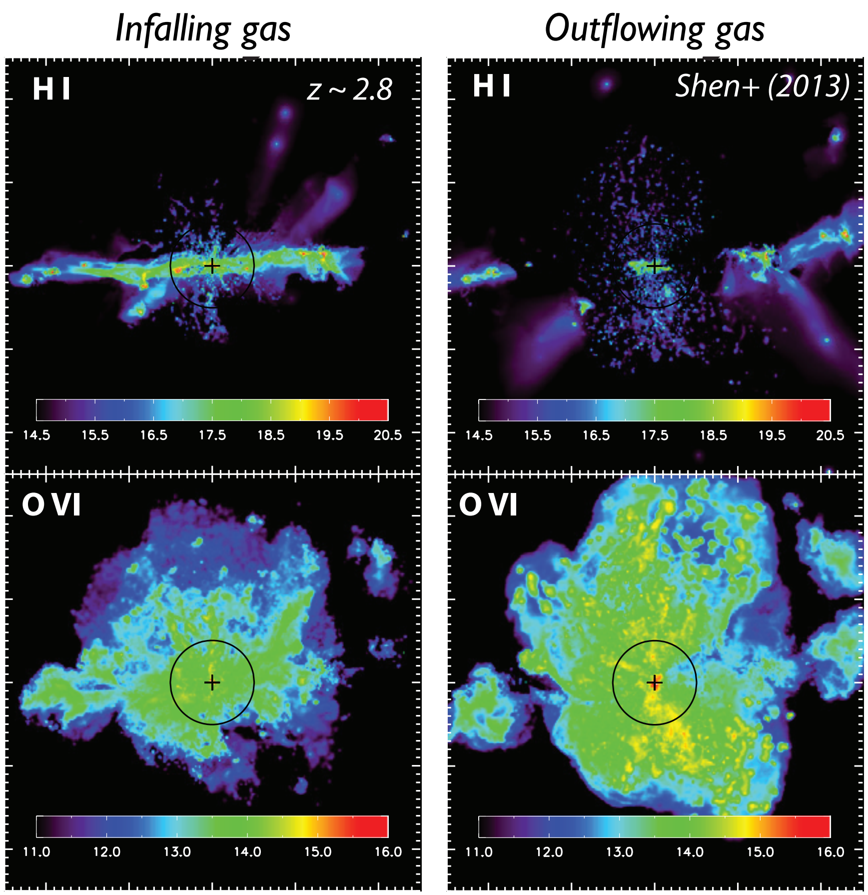
# Access to λ ~ 1000 Å is critical



Qu & Bregman (2017)



# The future: mapping the origins of the CGM gas




*Higher ionization states more directly probe the driving fluid, the more diffuse CGM.*

We want to **map** the CGM as a function of ***ionization state*** and ***metallicity***.

**This means:**

– Developing better statistical maps of the CGM with galaxy properties, etc. (ala COS-Halos).

– Directly mapping absorption lines toward many sight lines in individual galaxies, headed toward tomography. (Not even done yet for M31.)

– Observing resolved galaxies at low redshift to connect to H I mapping. *(21-cm won't get <few x $10^{17}$ $cm^{-2}$.)*

***– Emission line imaging.***

**Critical capabilities:**

***– Large aperture (sensitivity).***

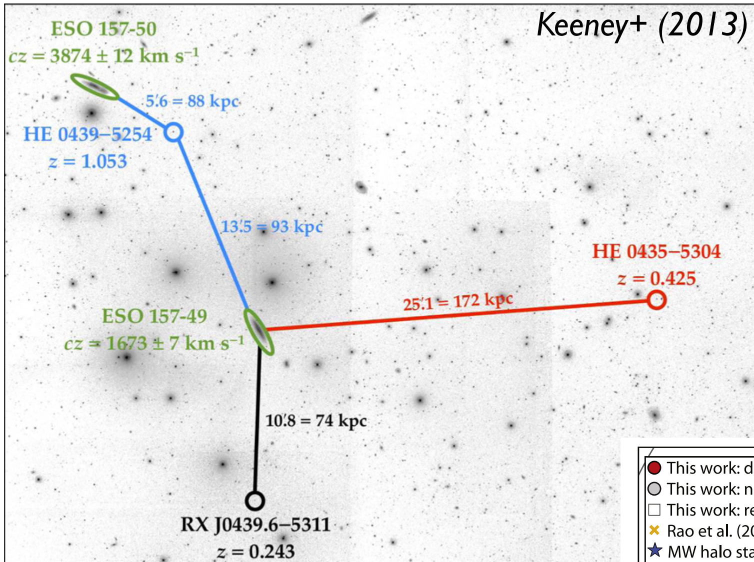
– High resolution (R>20,000).

– FUV capability to ~1000 Å.

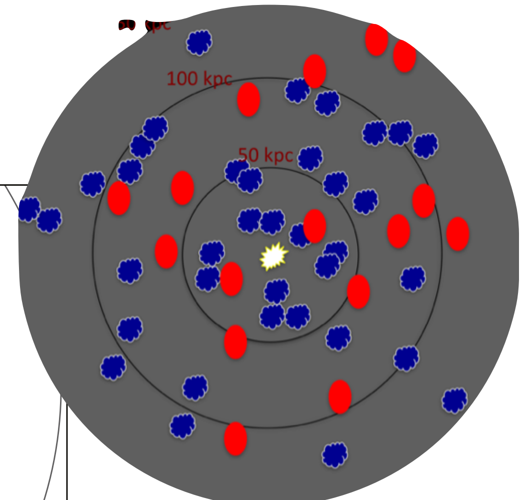
– Efficient NUV capabilities to 3000 Å (Lyα).

– …or UV imaging sensitivity, perhaps spectral image slicers or narrowband filters.

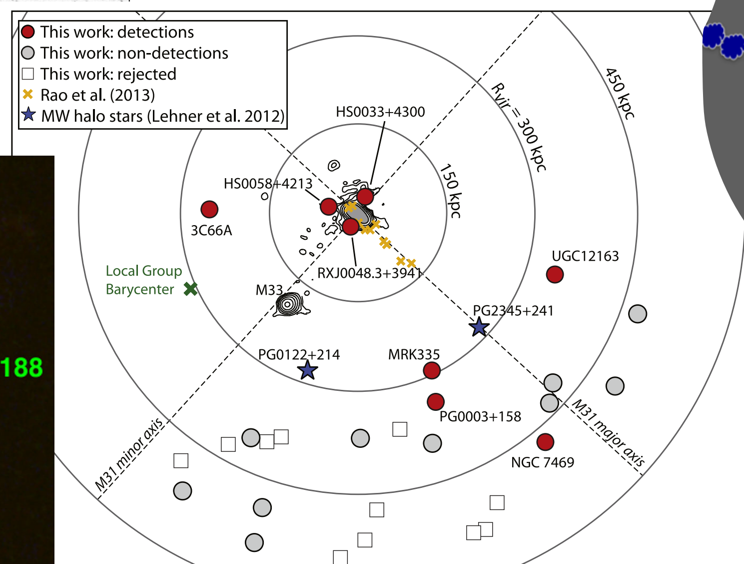
# The future: mapping the origins of the CGM gas



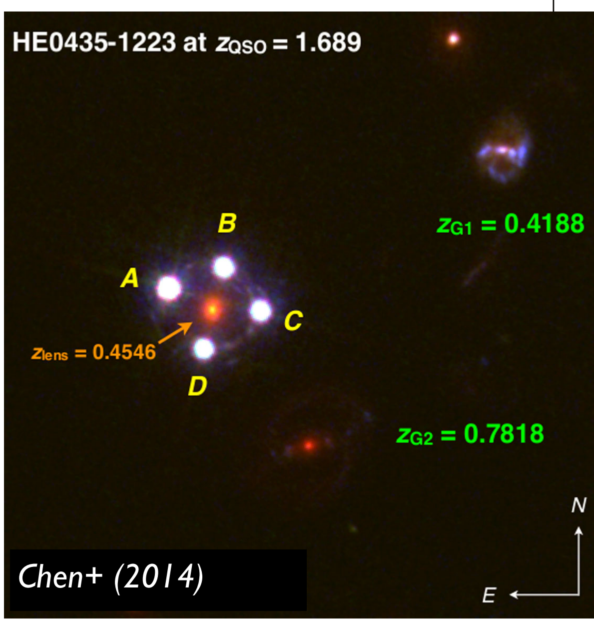

We want to **map** the CGM as a function of ***ionization state*** and ***metallicity***.




Tumlinson+ (2011, 2013)



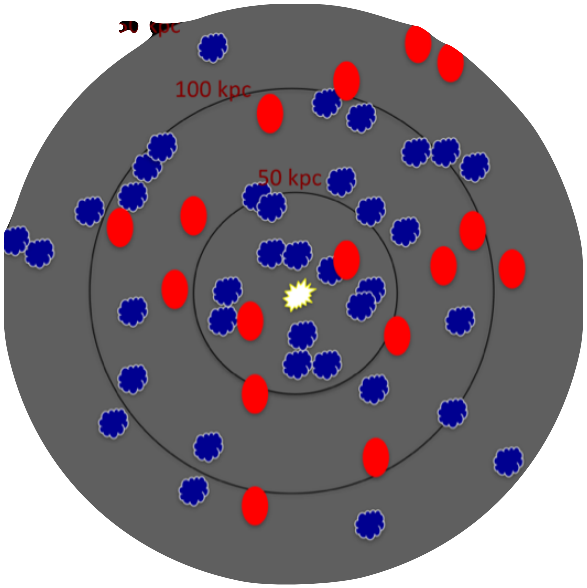

Lehner+ (2015)




Zahedy, Chen, et al.

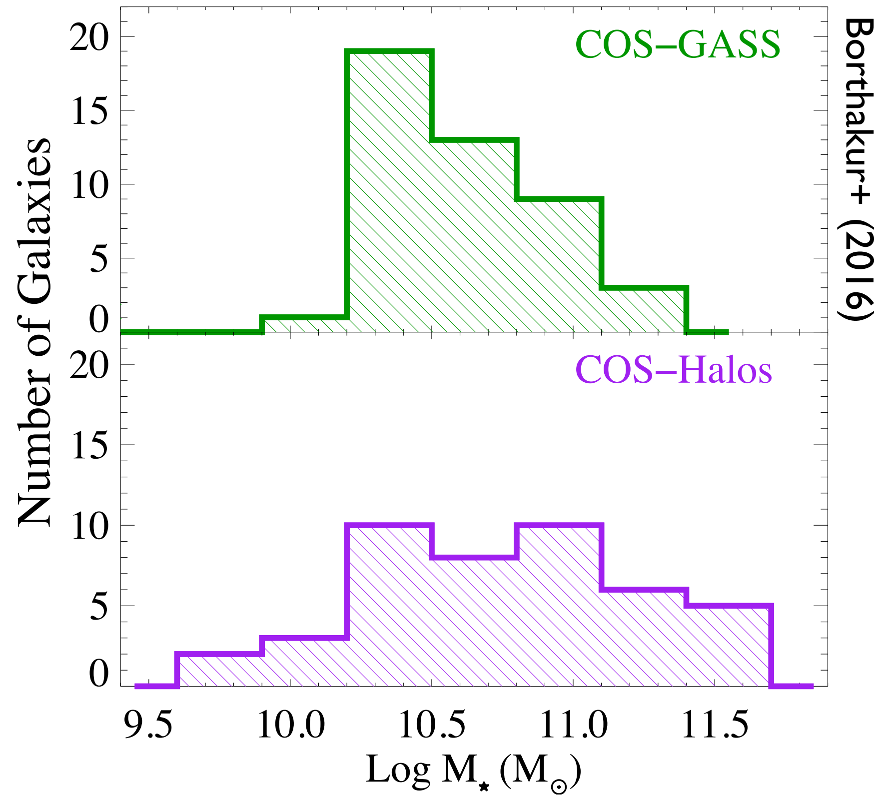
***Why do we need more of this if we have samples like this from HST?***

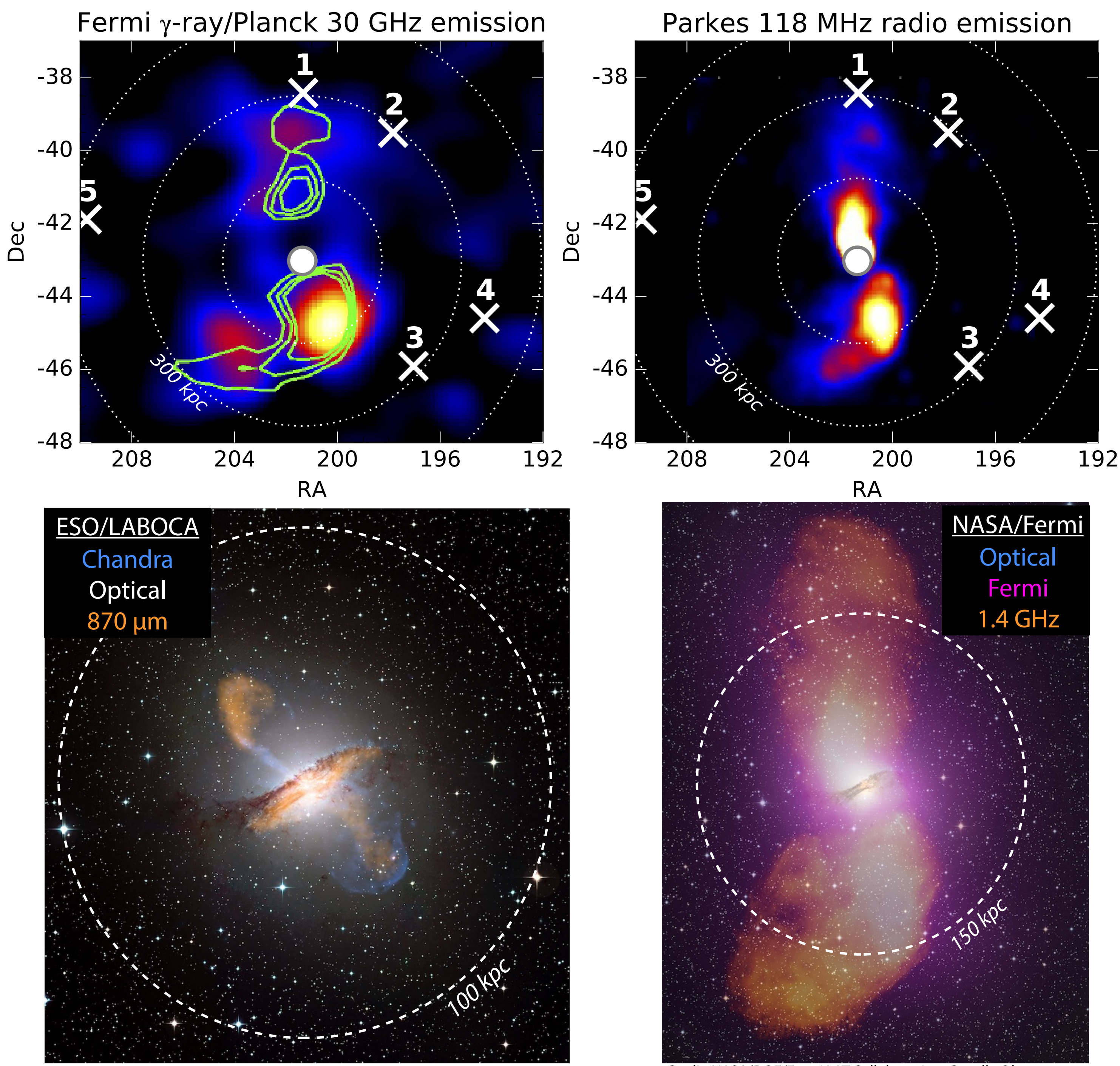
# The future: mapping the origins of the CGM gas




*Why do we need more of this if we have samples like this from HST?*

This is actually a very small sample if we want to understand the scaling relations in galaxies.

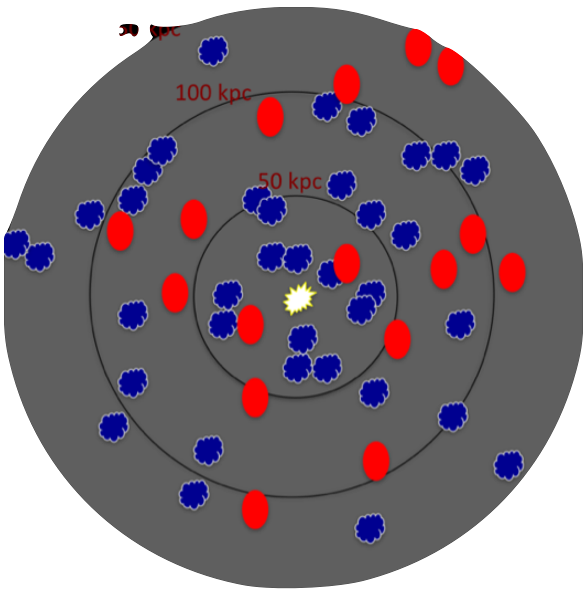


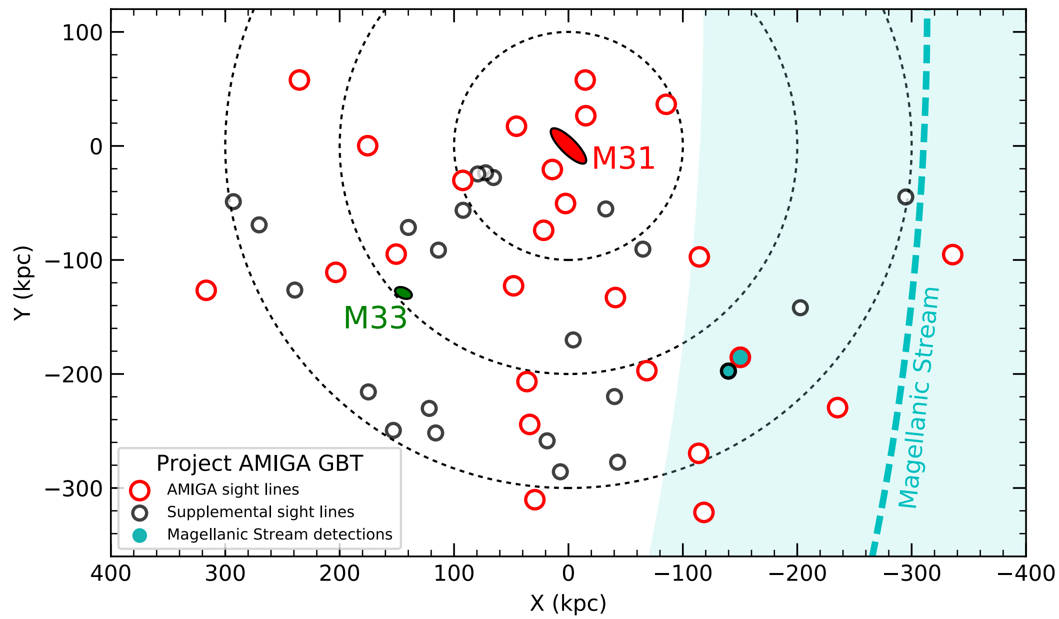


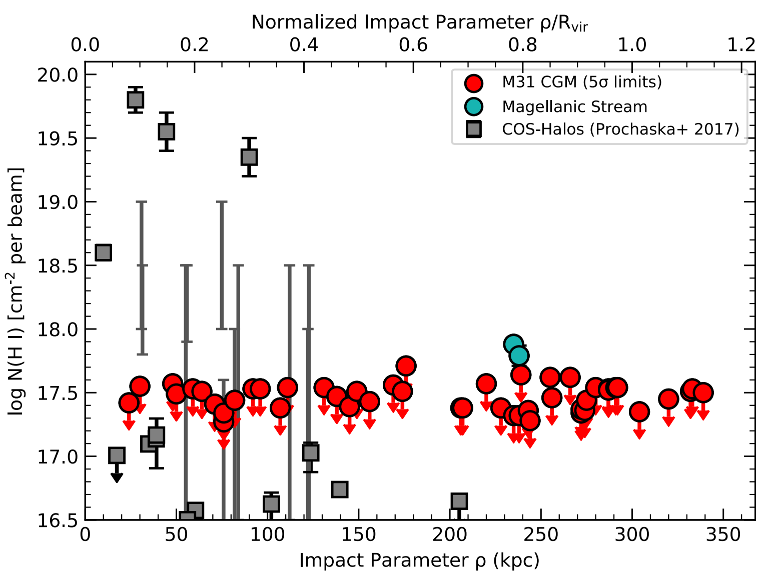

Credit: ESO; NASA

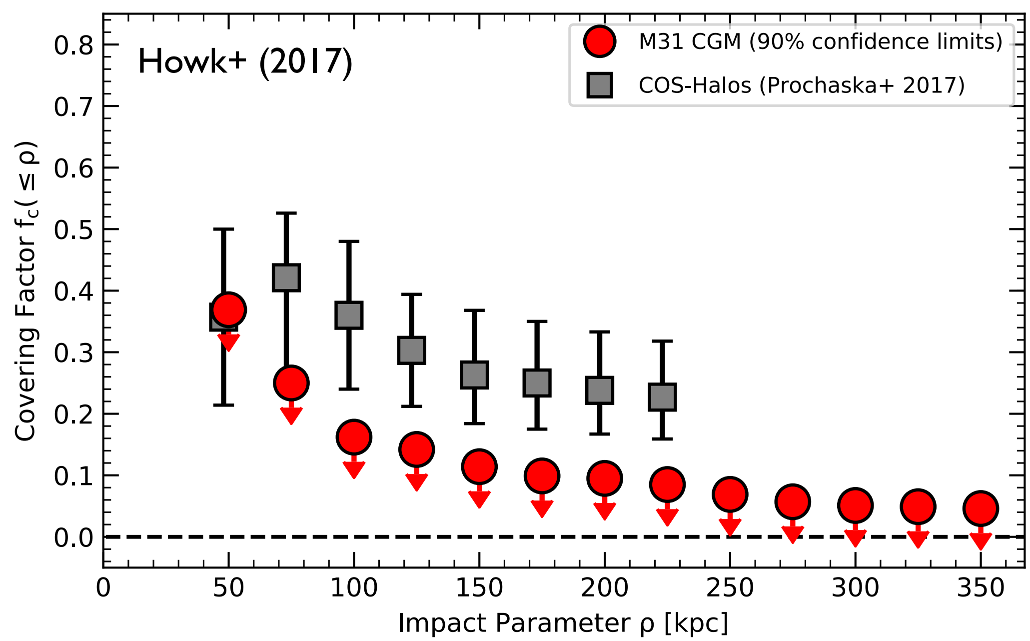
Credit: NASA/DOE/Fermi LAT Collaboration, Capella Observatory

# The future: mapping the origins of the CGM gas

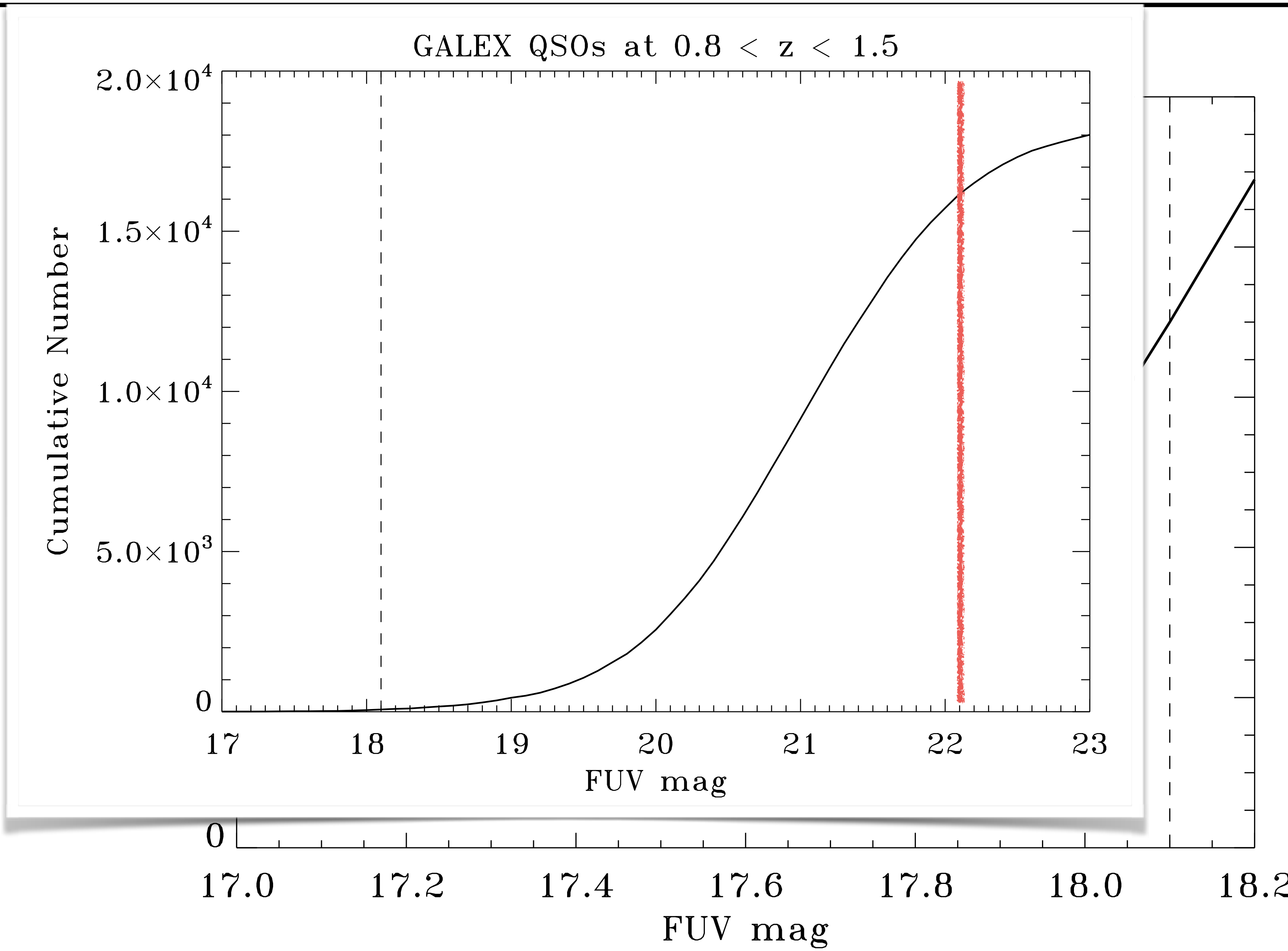


# Absorption line tomography of galaxy halos enabled by LUVOIR.



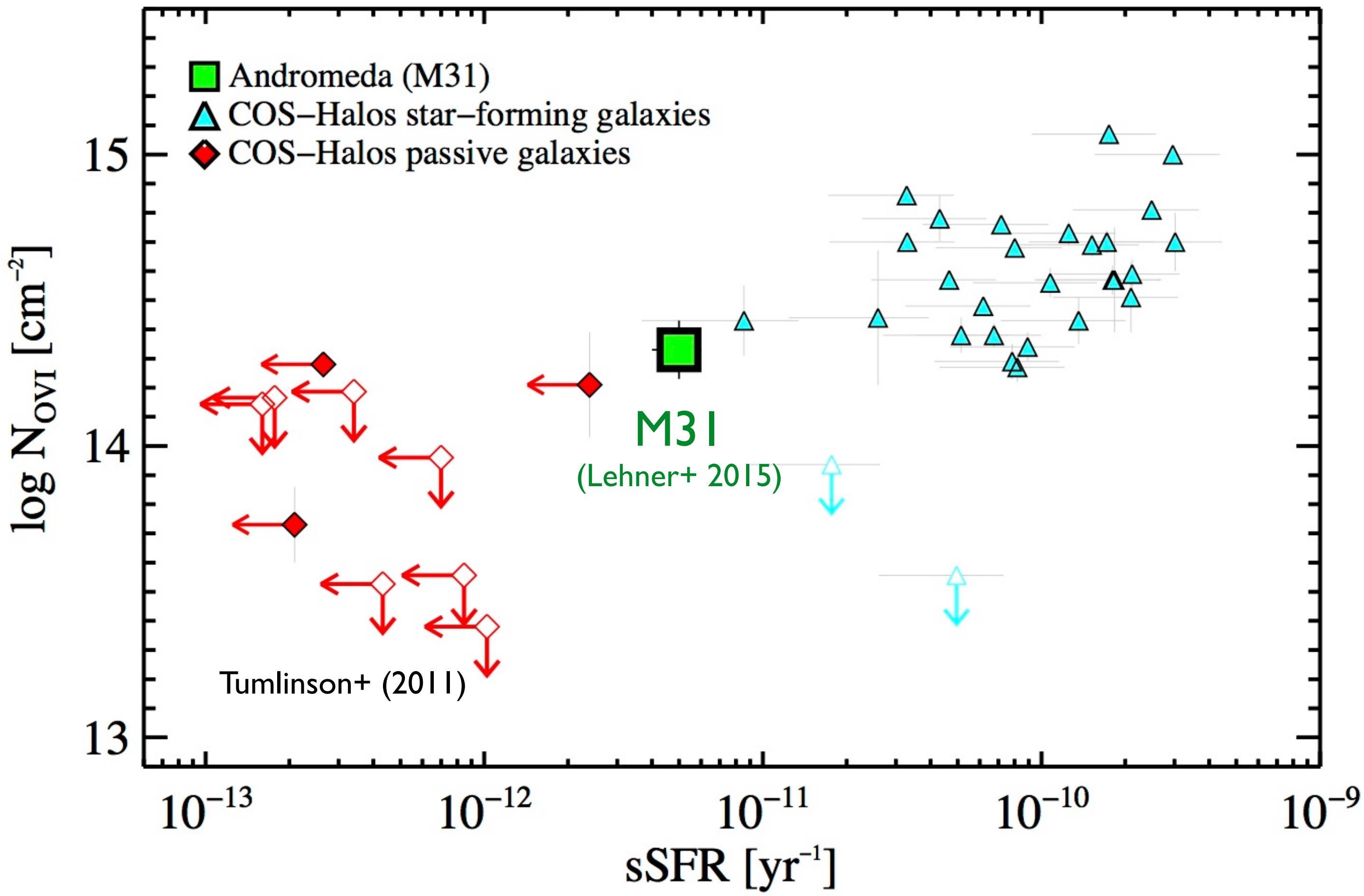
Each HST spectrograph had a factor of 10 improvement over its predecessor

**<u>GHRS</u>**
*10x spectral resolution of IUE
*At R ~ 100,000, $\Delta\lambda$ ~ 7 Å!

**<u>STIS</u>**
*~30x spectral coverage
for R ~ 100,000

**<u>COS</u>**
* ~10x sensitivity, at lower R
* > 10x greater observable sample
of objects!

# Mapping the origins of stars in galaxies means imaging the CGM

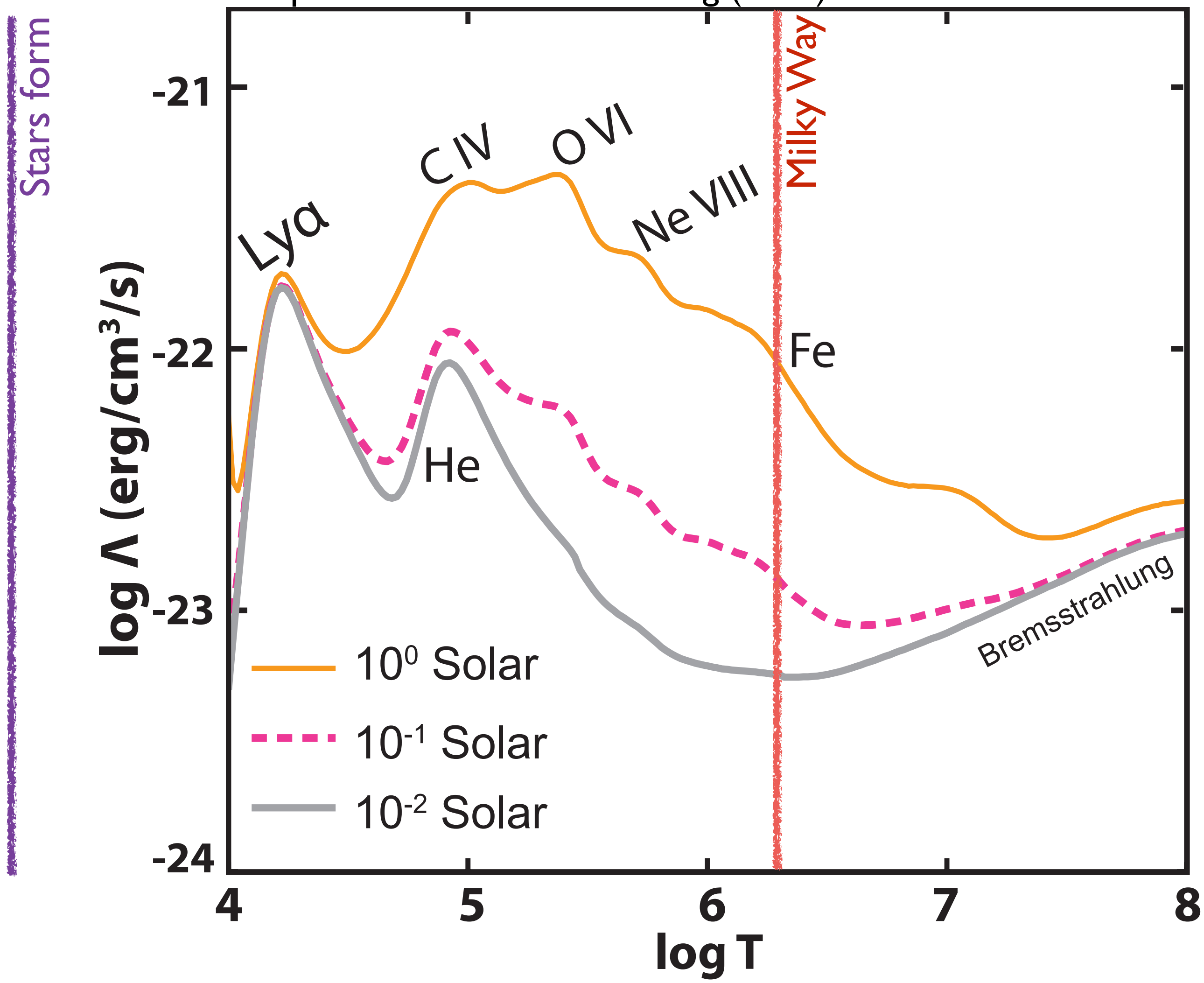



The presence and quantity of "warm" metals is strongly correlated with star formation properties of galaxies.

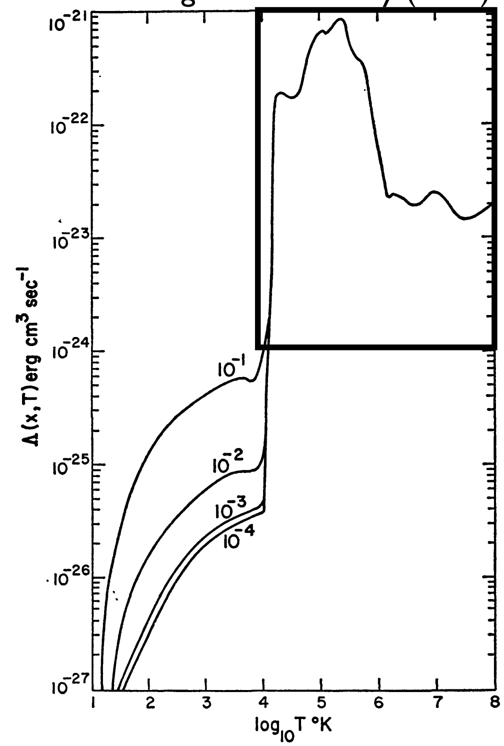
…but it is not for H I (Thom+ 2012).

# Mapping the origins of stars in galaxies means imaging

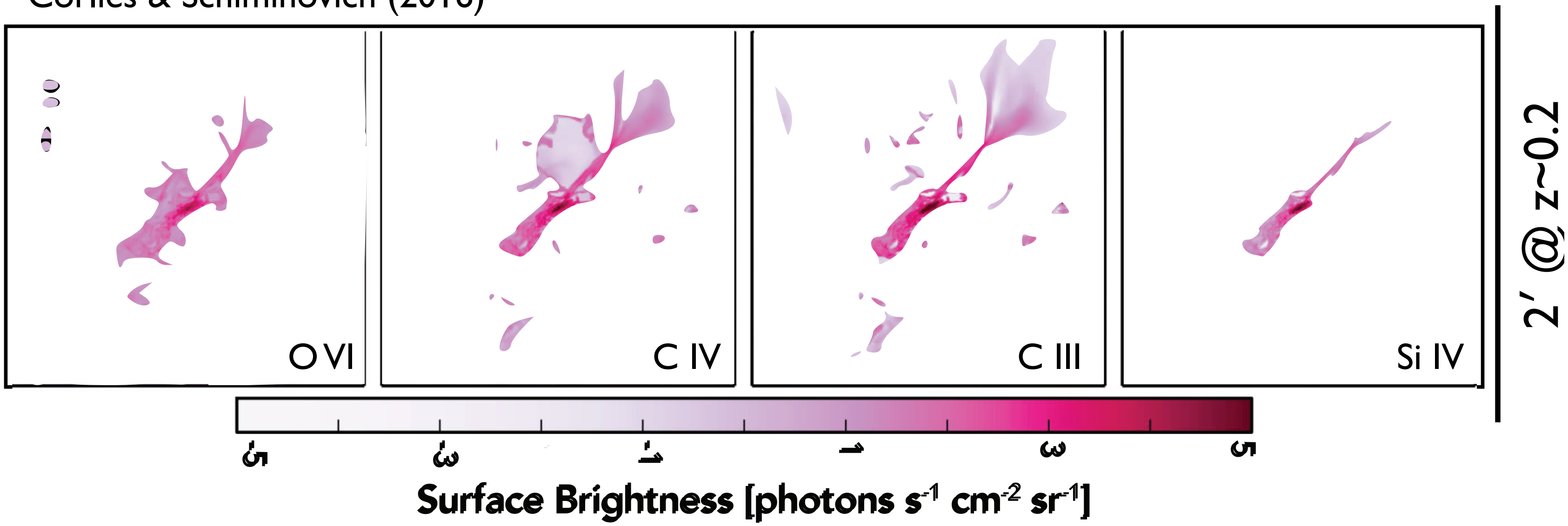
Adapted from Gnat & Sternberg (2007)

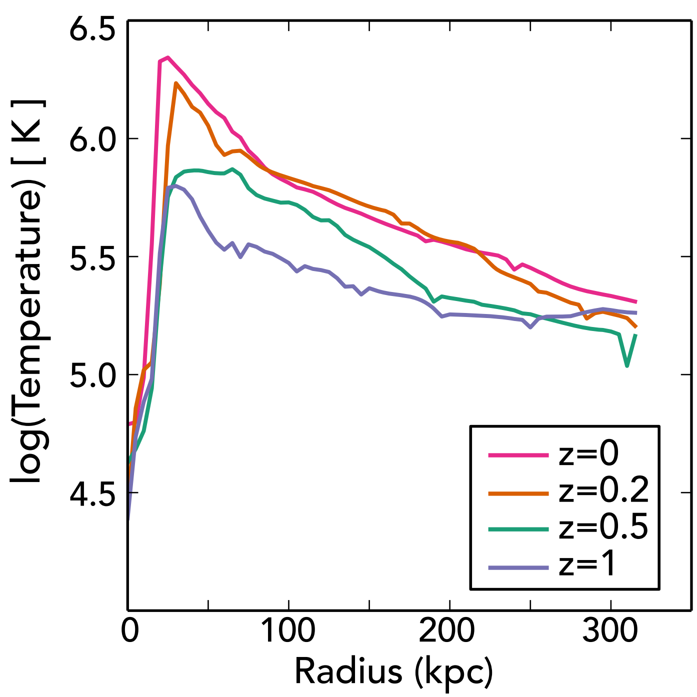



Dalgarno & McCray (1972)



Corlies & Schiminovich (2016)



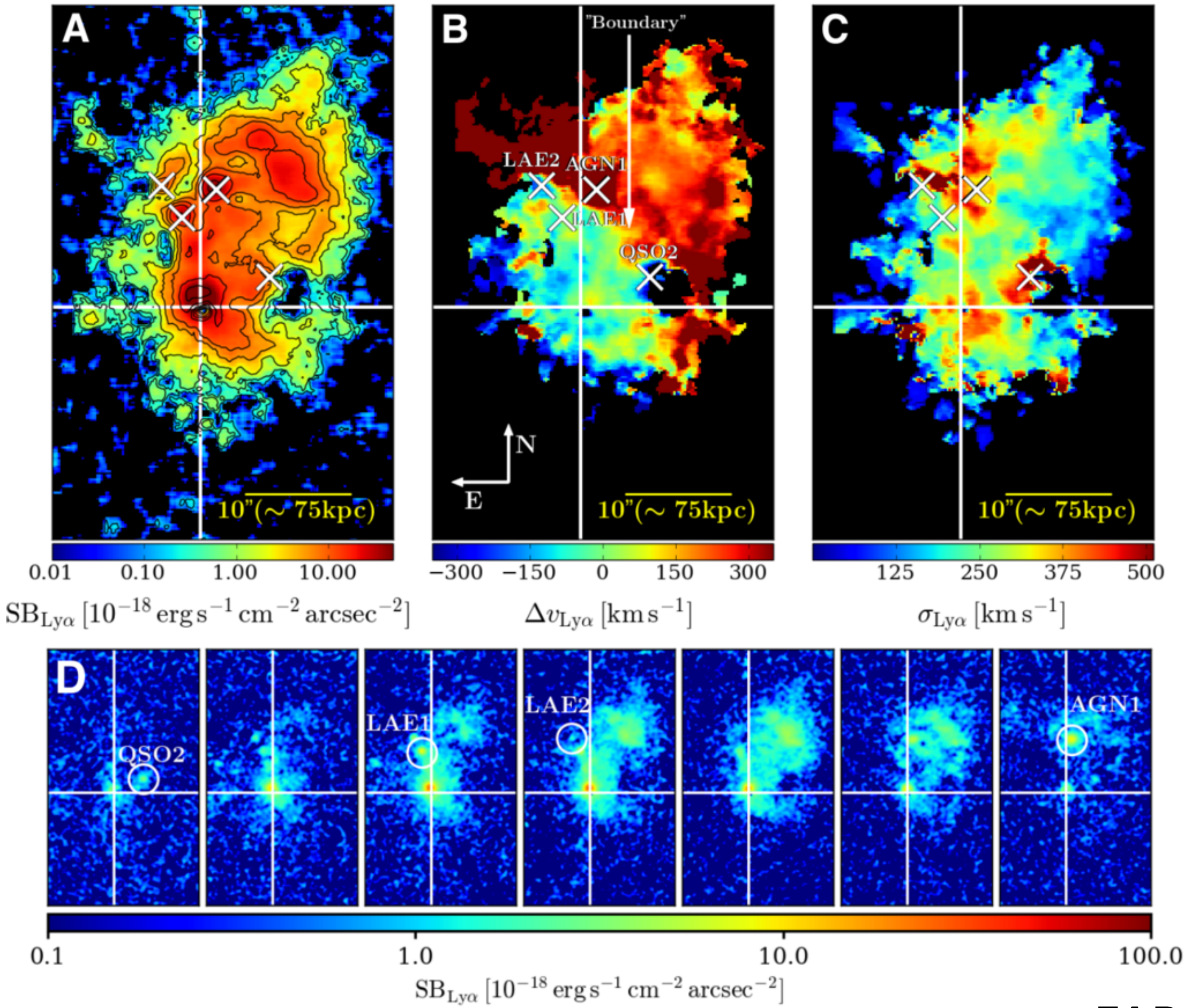

**Morphological information –**
Where are the filaments and winds?

**Cooling rates –**
Do galaxies acquire their gas from the CGM? Do winds lose their energy to radiation?

**Physical Scales –**
What are the relevant length, density scales for halo structures? Pressures, temperatures?

*See also van de Voort & Schaye (2013), Bertone & Schaye (2012)*

# The "cosmic web" in Lyα, lit up by QSOs/AGNs

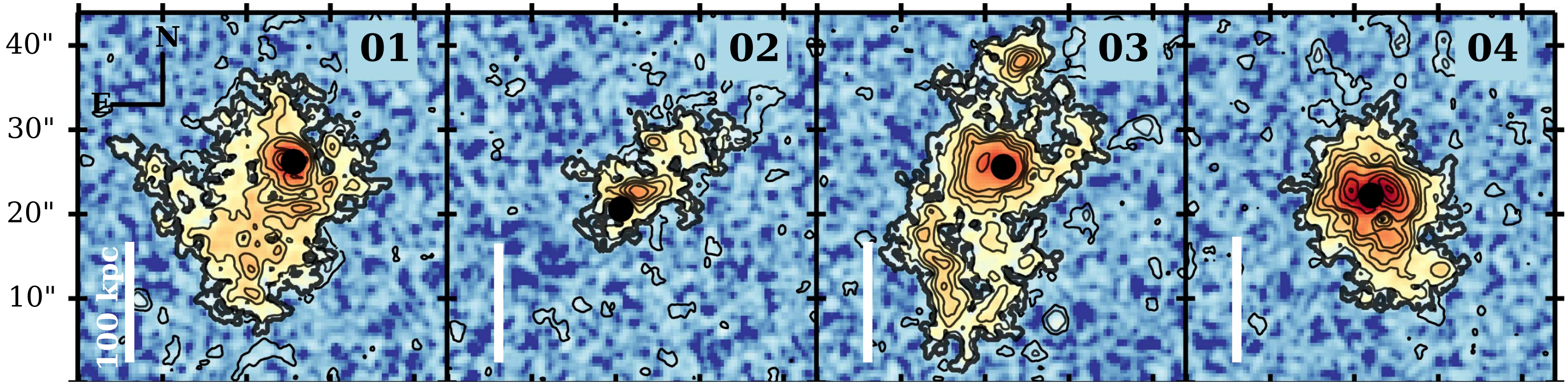


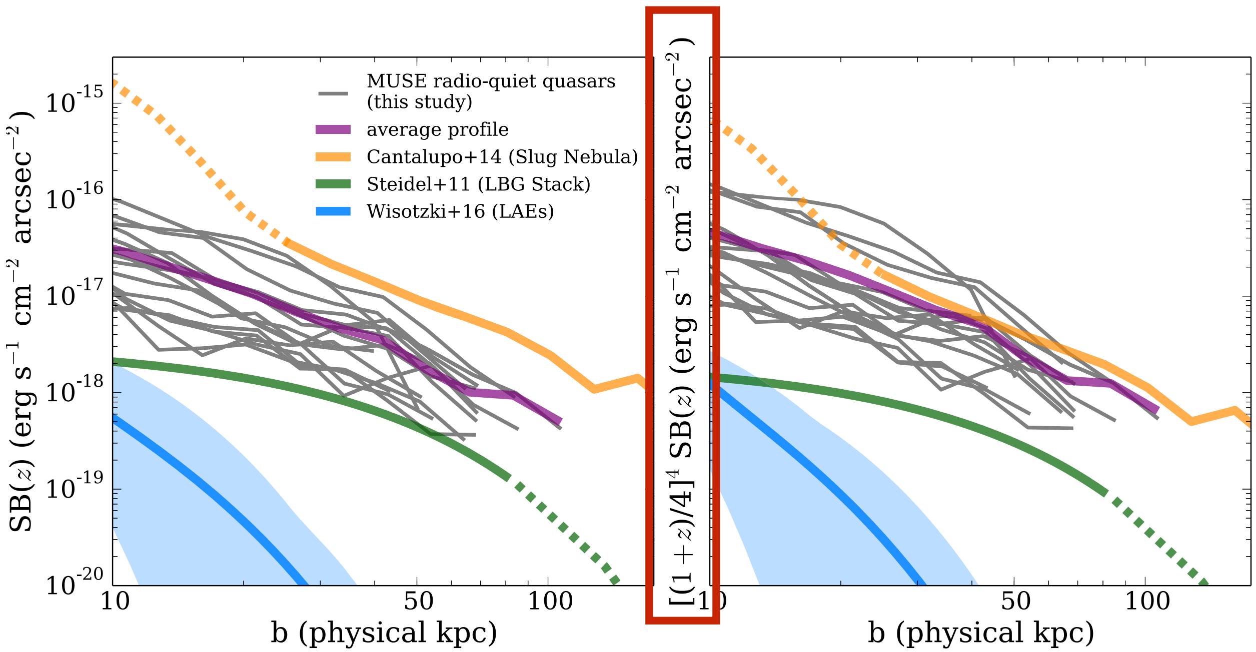

**FABulous Nebula**

Courtesy Fabrizio Arrigoni

# Low-redshift gives access to metal tracers in emission

Borisova+ (2016)




Low backgrounds, FUV wavelength access, low $(1+z)^4$ make this problem a tempting target for LUVOIR.

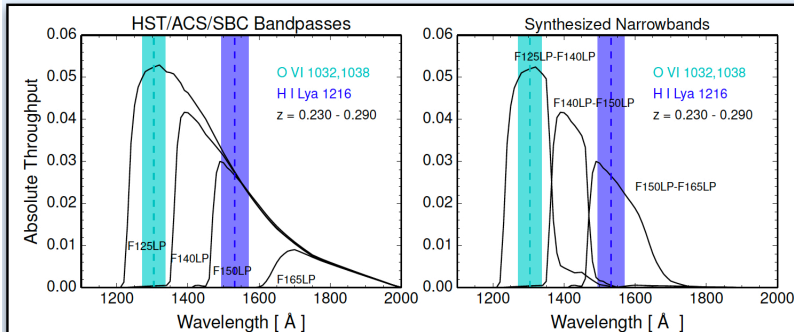
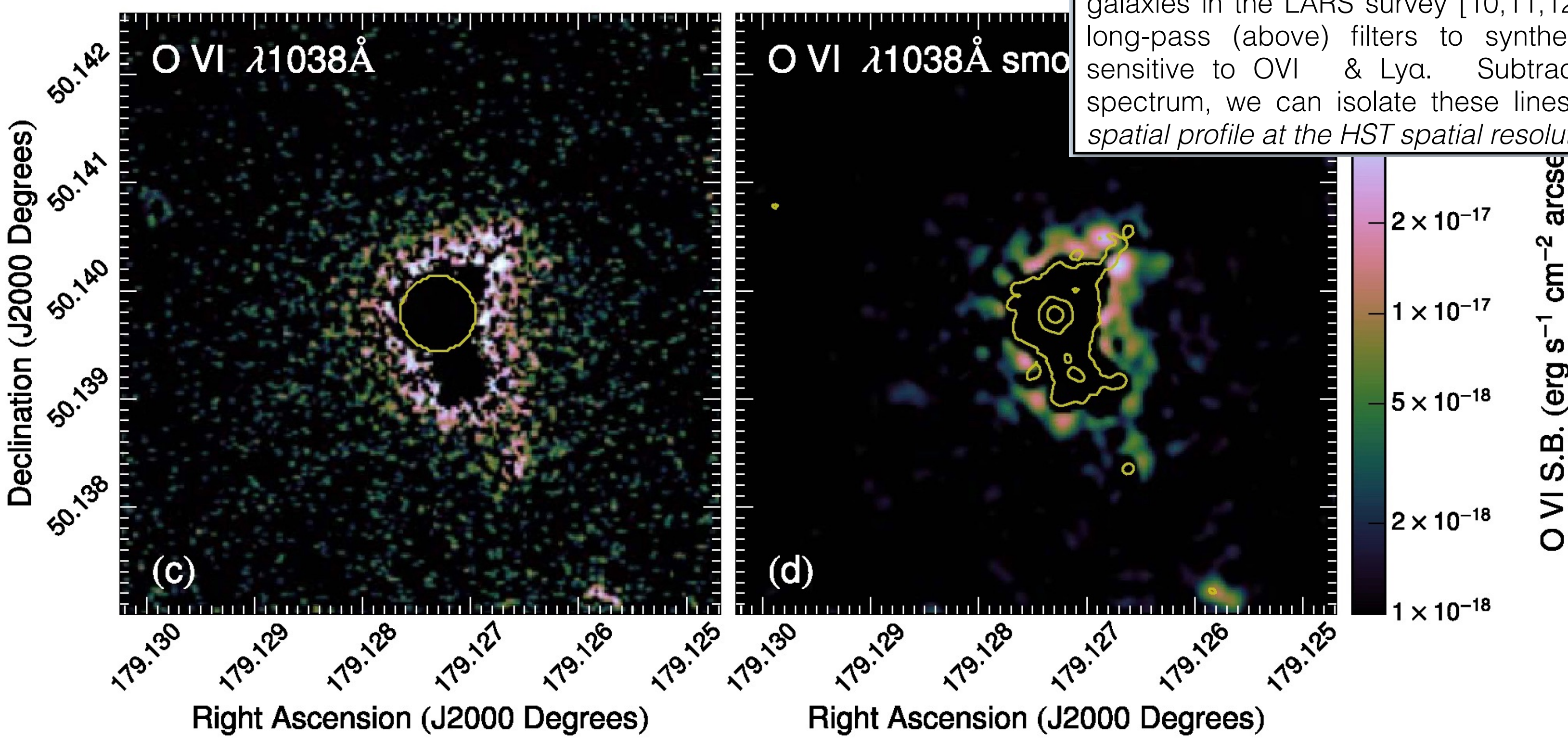
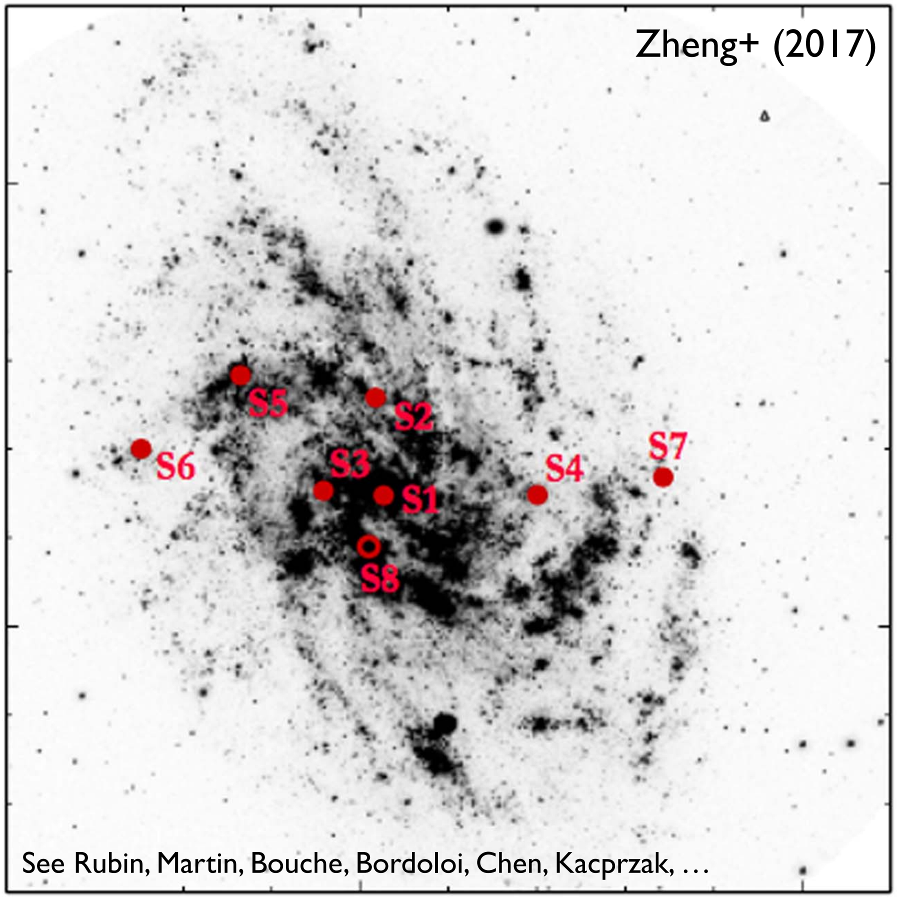



**Figure 1:** ***Synthesized OVI Narrowband*** — Applying a methodology first used to imaging HI Lyα in low-redshift galaxies in the LARS survey [10,11,12], we combine SBC long-pass (above) filters to synthesize a narrowband sensitive to OVI & Lyα. Subtracting the underlying spectrum, we can isolate these lines and *image the full spatial profile at the HST spatial resolution.*

Hayes+ (2016)



# The future: probing origins of galactic outflows




*Imagine 10s of individual UV slits for which we obtain R~5000+ spectra.*

**Especially powerful on larger scales against redshifted galaxies for mapping O VI, H I absorption.*

We want to map the origins of outflows across galaxies, understanding the dynamics of both **fountains** and **winds**.

**This means:**

– Using *down-the-barrel* experiments to trace outflows at their source against individual star forming regions.

– Leveraging multi-object capabilities.

– Coupled with background QSO galaxy spectroscopy.

**Critical capabilities:**

– Multi-object capability.

– Moderate resolution (R ~ 5000+).

# An HST *Pathfinder* Mode: Preparing the case for LUVOIR

The case is made easier if the parameters can be constrained ahead of time.

- How weak is the hot gas absorption from the halos of galaxies?
- Can we detect emission from the hot halo of a galaxy?
- …

# An HST *Legacy* Mode: Preparing for the Abyss

We will have a decade without traditional access to the UV. What keeps the science progressing during that time?

- G140L survey of a uniform sample of Local Group star forming regions.
- Comprehensive survey of WD metals
- UV irradiance / variability in planet host stars across HR diagram [e.g., K. France MUSCLES survey]
- Variability survey of debris disk absorption
- Uniform spectroscopy of top 10 QSOs at z>1 at high S/N to survey EUV transitions. [H.W. Chen Cycle 25 program]

Done through community working groups and the continued availability of **extra large proposal** categories.

**What cool things can we do with LUVOIR?**

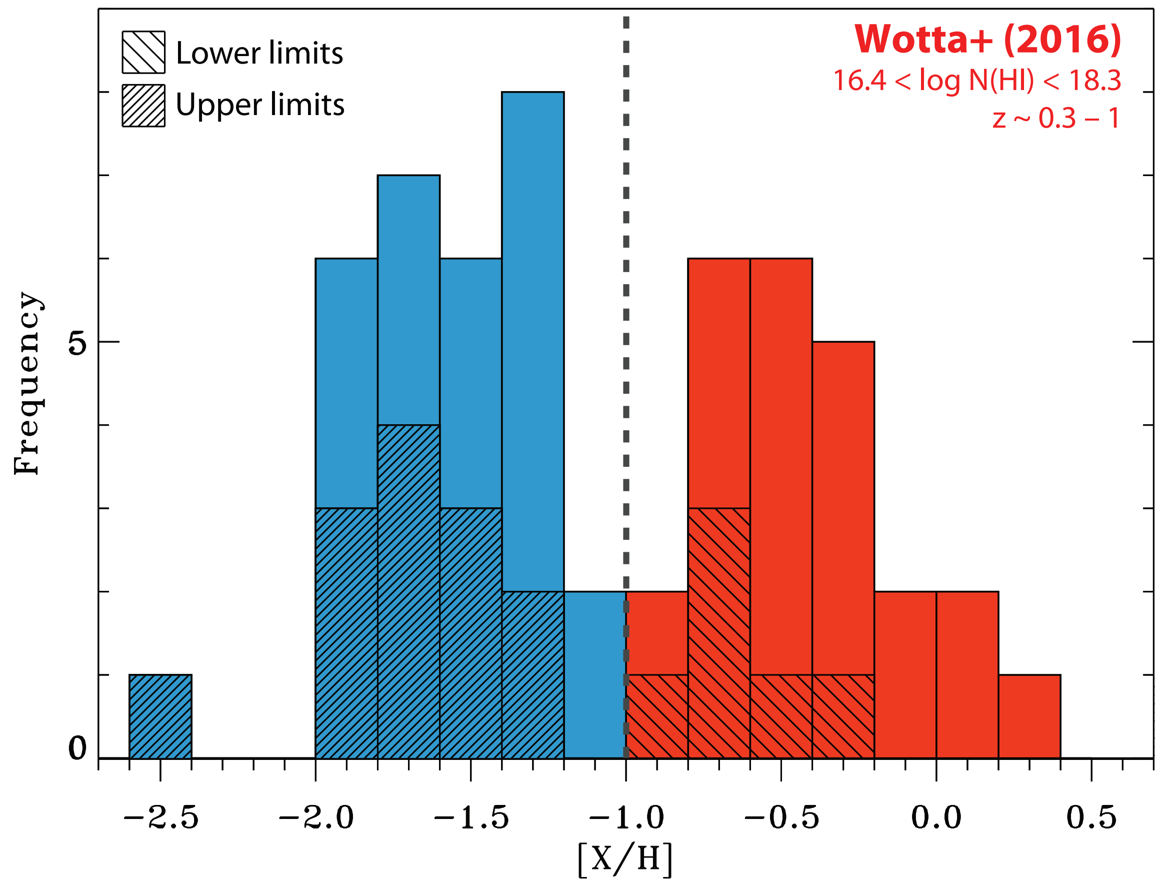
Plenty!!
And the STDT is seeking science input now…

**What do we need to get ready for and scope the design requirements of LUVOIR?**

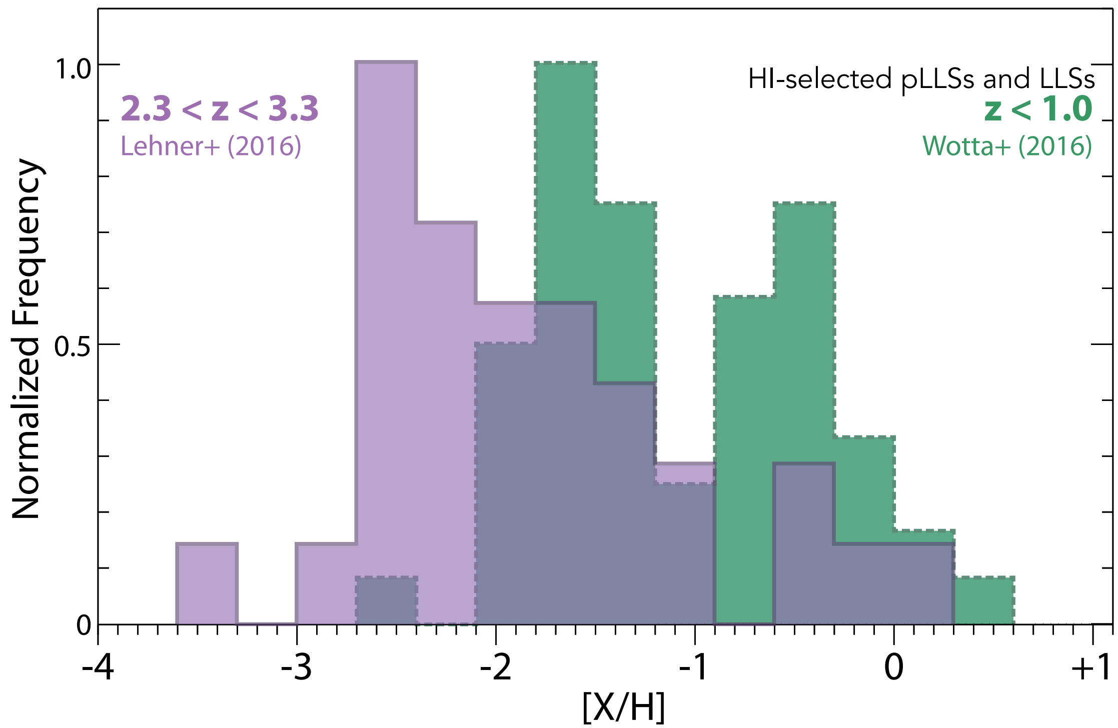
Let's test the more extreme cases to see what can be done

**What legacy do we want to leave for our decade without UV access?**

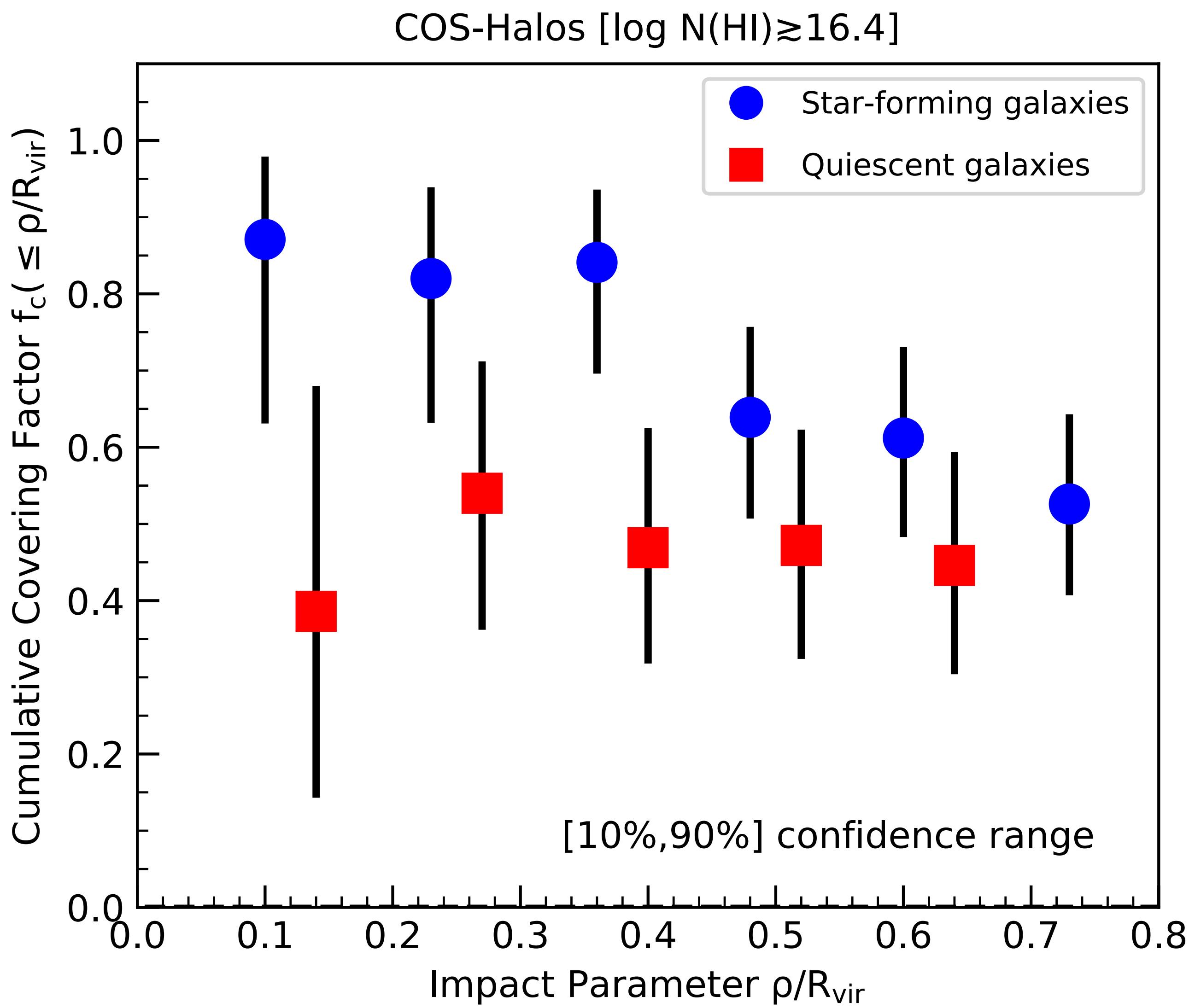
Let's decide this within our communities, seek a continued very large opportunity.



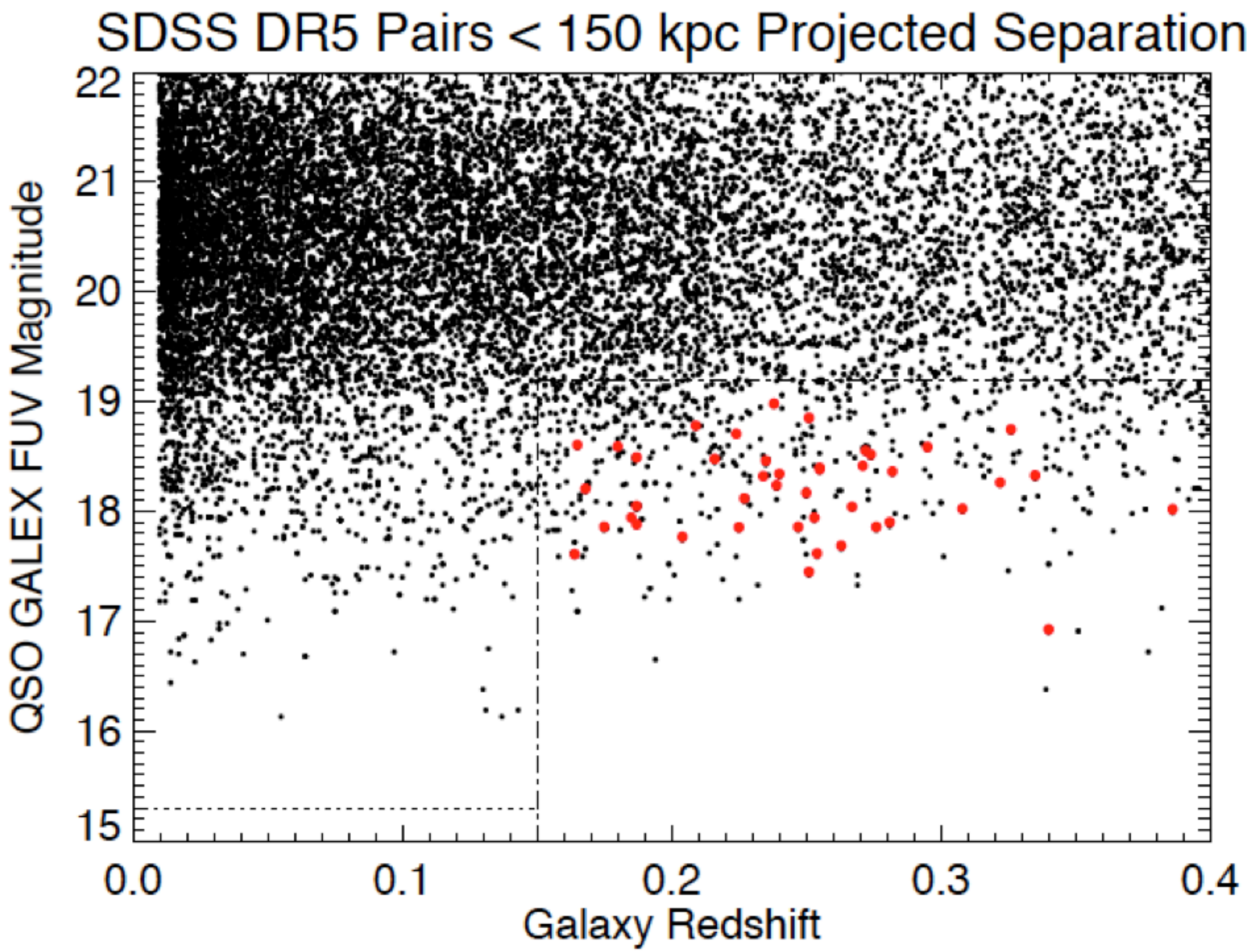
Lower limits
Upper limits
Wotta+ (2016)
16.4 < log N(HI) < 18.3
z ~ 0.3 – 1
Frequency
5
0
−2.5
−2.0
−1.5
−1.0
−0.5
0.0
0.5
[X/H]



HI-selected pLLSs and LLSs
2.3 < z < 3.3
Lehner+ (2016)
z < 1.0
Wotta+ (2016)
Normalized Frequency
1.0
0.5
0
-4
-3
-2
-1
0
+1
[X/H]



COS-Halos [log N(HI)≳16.4]
Star-forming galaxies
Quiescent galaxies
[10%,90%] confidence range
Cumulative Covering Factor $f_c(\leq \rho/R_{vir})$
Impact Parameter $\rho/R_{vir}$
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8




Scowen+ (arXiv:1611.09736)